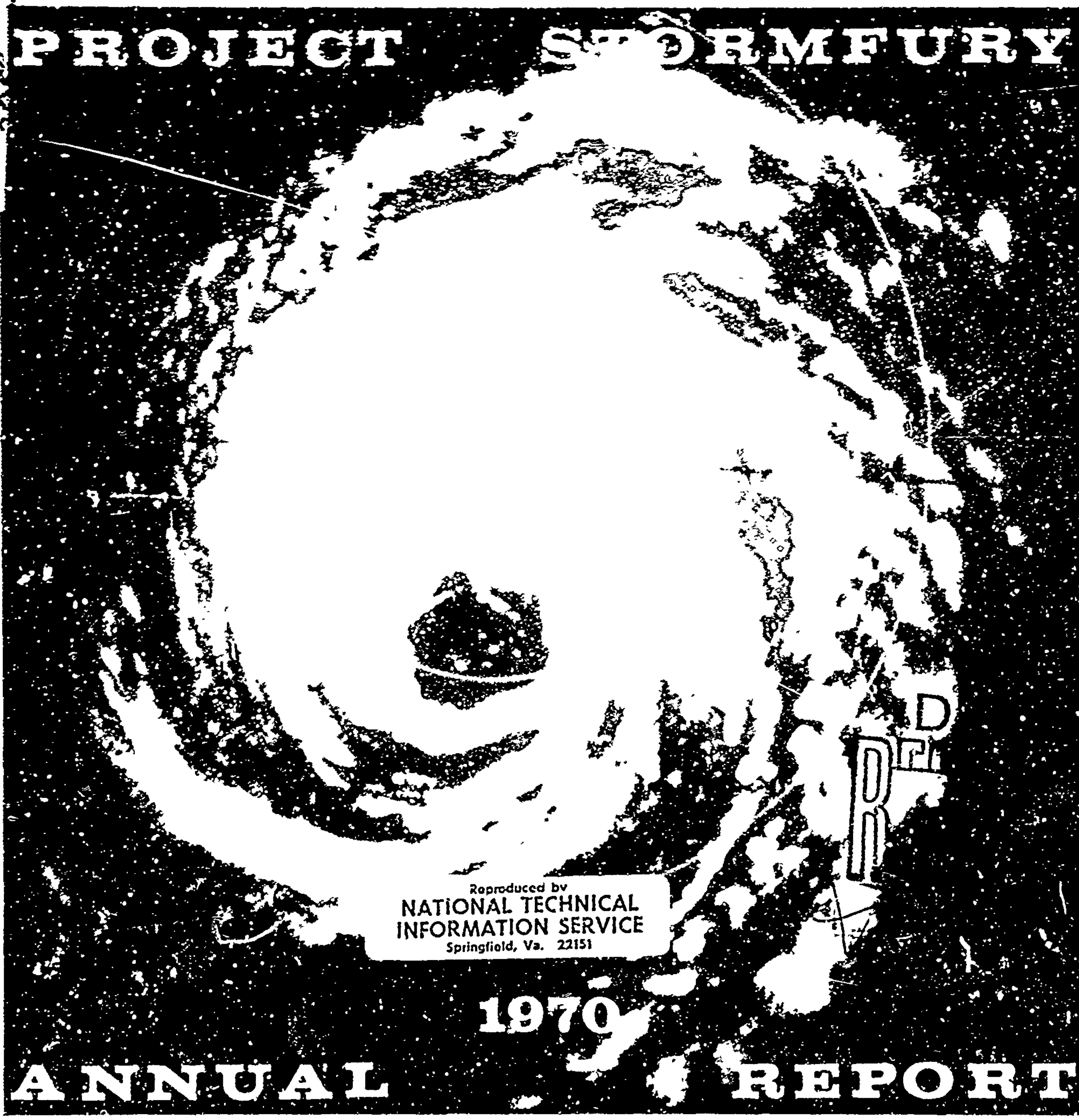
Project STORMFURY — 1970

U.S. DEPARTMENT OF THE NAVY
J. H. CHAFEE, Secretary

Naval Weather Service Command
W. J. KOTSCH, Rear Admiral, USN, Commander

U. S. DEPARTMENT OF COMMERCE
M. H. STANS, Secretary

National Oceanic and Atmospheric Administration
R. M. WHITE, Administrator



MIAMI, FLORIDA
MAY 1971

169

STANDARD TITLE PAGE FOR TECHNICAL REPORTS	1. Report No. NOAA-71083002	2. Govt. Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Project STORMFURY - Annual Report 1970			5. Report Date May 1971
			6. Performing Organization Code
7. Author(s) U.S. Naval Weather Service Command and NOAA, National Hurricane Research Lab.			8. Performing Organization Rept. No.
9. Performing Organization Name and Address U.S. Naval Weather Service Com. Department of the Navy Washington Navy Yard Washington, D.C. 20390 / NOAA National Hurricane Research Laboratory P.O. Box 8265 University of Miami Branch Coral Gables, Fla. 33124			10. Project/Task/Work Unit No.
			11. Contract/Grant No. Grant NSF-G-17993
12. Sponsoring Agency Name and Address Same and National Science Foundation			13. Type of Report & Period Covered Annual Report 1970
			14. Sponsoring Agency Code
15. Supplementary Notes			

16. Abstract

Project STORMFURY is a joint Department of Commerce (NOAA)-Department of Defense (Navy) program of scientific experiments designed to explore the structure and dynamics of tropical cyclones and their potential for modification. The Project which was formally established in 1962 has as its principal objective experimentation directed towards changing the hurricane's energy exchange by strategic seeding from aircraft with silver iodide crystals. The crystals are dispensed from pyrotechnic devices developed by the U.S. Navy. The hypothesis calls for a measurable decrease in the maximum wind velocities near the center of the storm. Navy and NOAA scientists and aircraft, supplemented by those of the U.S. Air Force, have cooperated in STORMFURY experimental operations since 1962 when the Project began. The 1970 hurricane season produced no tropical cyclones which were eligible for seeding experiments. In spite of this, or perhaps because of it, the 1970 season was undoubtedly the most productive research period for Project STORMFURY to date. The results of these various research activities are given.

17. Key Words and Document Analysis. 17a. Descriptors

Weather modification
Hurricanes
Tropical cyclones
Cloud physics
Pyrotechnis
Cloud seeding
Research projects
Evaluation

17b. Identifiers/Open-Ended Terms

Project STORMFURY
Annual Report, 1970

17c. COSATI Field/Group 4A; 4B

18. Distribution Statement Copies available at either address appearing in block 9 Robert R. Freeman	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 168
	20. Security Class (This Page) UNCLASSIFIED	22. Price

FORM CFSTI-35 (4-70) USCOMM-DC 65002-P70

U.S. DEPARTMENT OF THE NAVY
J. H. CHAFEE, Secretary

Naval Weather Service Command
W. J. KOTSCH, Rear Admiral, USN, Commander

U. S. DEPARTMENT OF COMMERCE
M. H. STANS, Secretary

National Oceanic and Atmospheric Administration
R. M. WHITE, Administrator

PROJECT STORMFURY ANNUAL REPORT 1970

MIAMI, FLORIDA
MAY 1971

Project STORMFURY was established by an Interdepartmental agreement between the Department of Commerce and the Department of Defense, signed July 30, 1962. Additional support has been provided by the National Science Foundation under Grant NSF-G-17993.

This report is the ninth of a series of annual reports to be prepared by the Office of the Director in accordance with the Project STORMFURY interdepartmental agreement.

Additional copies of this report may be obtained from:

U. S. Naval Weather Service Command
Department of the Navy
Washington Navy Yard
Washington, D. C. 20390

or

National Hurricane Research Laboratory
P. O. Box 8265, University of Miami Branch
Coral Gables, Florida 33124.

NOTICE

TABLE OF CONTENTS

PROJECT STORMFURY ANNUAL REPORT - 1970

INTRODUCTION

The apparently successful seeding operations on Hurricane Debbie in 1969 made it most urgent that similar experiments be carried out on a 1970 storm to provide further evaluation of the effectiveness of the technique. The 1970 hurricane season, however, produced no tropical cyclones which were eligible for seeding experiments. In spite of this, or perhaps because of it, the 1970 season was undoubtedly the most productive research period for Project STORMFURY to date.

Even though no eligible storm developed, the STORMFURY forces did operate together during dry-run exercises, cloudline experiments, and on a data-gathering mission in Tropical Storm Dorothy. The dry-run exercises were conducted from the Naval Station Roosevelt Roads, Puerto Rico, on 21 through 24 July, and these were followed immediately by the cloudline exercises during the last 6 days of the month. The STORMFURY forces were again deployed to Puerto Rico when it appeared on 19 August that Tropical Storm Dorothy might develop into a hurricane and move into the Caribbean. Even if she did not intensify and become eligible for a modification experiment, she could still have provided a good storm for a STORMFURY monitoring mission if her intensity remained sufficiently stable. On this basis, the STORMFURY forces moved to Puerto Rico on 20 August. Dorothy, however, started to weaken after crossing the island of Martinique, and the operation reverted to a data-gathering mission to provide badly needed information on a tropical wave.

With the lack of eligible storms in 1970, the hurricane research efforts were intensified and carried out without operational interruptions. The results of these various research activities are extremely interesting particularly as they relate to future STORMFURY operations, and the more significant results are given in the Appendices to this report. Of special interest in this connection is Appendix B which details a new and better explanation for the apparent success of the 1969 "Debbie" experiments than was possible with the pre-existing hypothesis.

The optimism generated by the "Debbie" work also resulted in increased emphasis being placed on the Project by the Government. In 1970 Project STORMFURY was designated a National Pilot Project by the Interdepartmental Committee for Atmospheric Science (ICAS), and some additional STORMFURY funding was made available in the FY-1971 budget of the Department of Commerce.

HISTORY AND ORGANIZATION

Project STORMFURY is a joint Department of Commerce (NOAA)-Department of Defense (Navy) program of scientific experiments designed to explore the structure and dynamics of tropical cyclones and their potential for modification. The Project which was formally established in 1962 has as its principal objective experimentation directed towards changing the hurricane's energy exchange by strategic seeding from aircraft with silver iodide crystals. The crystals are dispensed from pyrotechnic devices developed by the U.S. Navy. The hypothesis calls for a measurable decrease in the maximum wind velocities near the center of the storm. Navy and NOAA scientists and aircraft, supplemented by those of the U.S. Air Force, have cooperated in STORMFURY experimental operations since 1961 when the first informal agreement was proposed. To date, the experiments conducted by the Project consist of:

Hurricane Esther - seeded in 1961 - Single seeding
Hurricane Beulah - seeded in 1963 - Single seeding
Tropical Cumulus Cloud Seedings - 1963
Tropical Cumulus Cloud Seedings - 1965
Tropical Cloudline Seedings - 1968
Tropical Cloudline Seedings - 1969
Hurricane Debbie Seedings - 1969 - Multiple seeding
Tropical Cloudline Seedings - 1970.

Since 1962, only two hurricanes have been seeded[1]. The results of the Hurricane Debbie multiple seeding experiments conducted on 18 and 20 August 1969, were extremely encouraging in that a decrease in the maximum wind velocity of the hurricane was observed on both days. Although by no means conclusive, these observations coupled with radar and other meteorological data strongly suggest that a modification to Hurricane Debbie was achieved. The exact amount of effect caused by seeding is still very difficult to determine due to the natural fluctuations which occur in each tropical cyclone.

The initial 1962 Project STORMFURY agreement between the Department of Commerce and the Department of the Navy covered 3 years and was renewed annually from 1965 to 1968. The 1969 renewal was extended to cover a 3 year period.

---

[1] See Project STORMFURY Annual Reports 1963 through 1969.

Dr. Robert M. White, NOAA Administrator, and Rear Admiral W. J. Kotsch, U.S. Navy, Commander Naval Weather Service Command, had overall responsibility for the cooperatively administered project.

The Project Director in 1970 was Dr. R. Cecil Gentry, Director of the National Hurricane Research Laboratory (NHRL), Miami, Florida. The Alternate Director was Dr. Harry F. Hawkins, also of NHRL. The Assistant Project Director and Navy Project Coordinator was Captain L. J. Underwood, U.S. Navy, Commanding Officer of the Fleet Weather Facility, Jacksonville, Florida (FLEWEAFAC JAX). The Alternate to the Assistant Project Director was Commander J. O. Heft, U.S. Navy, also of FLEWEAFAC JAX. Mr. Jerome W. Nickerson, Navy Weather Research Facility, Norfolk, Virginia (WEARSCHFAX), was Technical Advisor to the Navy; Dr. S. D. Elliott, Jr., Naval Weapons Center, China Lake, California, was NWC Project Officer; Mr. Max Edelstein, Naval Weather Service Command Headquarters, Washington, D.C., was assigned liaison duties representing the Navy; and Mr. William D. Mallinger (NHRL) was assigned liaison duties for the Project Director and NOAA and acted as Data Quality Control Coordinator.

PROJECT STORMFURY ADVISORY PANEL

The Advisory Panel of five members is representative of the scientific community and provides guidance through its consideration of various scientific and technical problems involved with the project. Their recommendations have proved to be of great value to the project since its inception.

The Panel reviews results from previous experiments, proposals for new experiments and their priorities, and makes recommendations concerning the effectiveness of data collection and evaluation, eligibility criteria for storms to be seeded, and other items as applicable.

During 1970, the Advisory Panel consisted of the following prominent scientists: Professor Noel E. LaSuer, Chairman (Florida State University), Professor Jerome Spar (Department of Meteorology and Oceanography, New York University), Professor Edward Lorenz (Department of Meteorology, Massachusetts Institute of Technology), Professor Charles L. Hosler (Dean, College of Earth and Mineral Sciences, Pennsylvania State University), and Professor James E. McDonald (Institute of Atmospheric Sciences, University of Arizona).

The Panel met in Miami on 29 and 30 September 1970 to discuss numerical hurricane modeling research and the simulated seeding experiments with the hurricane models conducted by Dr. S. L. Rosenthal and his group at NHRL.

The Panel again met in Washington, D.C., on 28-30 January 1971. The first day, the Panel members participated in a briefing to NOAA about research on "Decision Analysis of Hurricane Modification" done at the Stanford Research Institute. The Panel meeting on 29 and 30 January was attended by representatives from cooperating agencies and included full discussions of research on past experiments and future plans for the Project. Professor Lorenz resigned from the Panel in October due to the pressure of other work in which he is engaged. He was replaced by Professor Norman A. Phillips (Department of Meteorology, Massachusetts Institute of Technology). Recommendations from the Panel meetings in Miami, Florida, and Washington, D.C., are included in this report as Appendix A.

PUBLIC AFFAIRS

A coordinated press release and fact sheet for STORMFURY were distributed to the media prior to the experimental season. Although no hurricane seeding opportunities occurred, the public affairs team was prepared to operate with a plan similar to that used during the "Debbie" experiments of 1969. Two seats on the Project aircraft were to be made available on a pool basis to media representatives. One seat was to go to a reporter and the other to a cameraman representing TV networks. Additional seats for the media may be possible for future operations if sufficient interest for additional coverage becomes apparent.

PYROTECHNIC DEVICES - SILVER IODIDE

The pyrotechnics prepared for the 1970 season were similar to the STORMFURY I unit used in the 1969 seeding experiments, but incorporated several improvements that made them safer to handle. This new unit, developed under the leadership of Dr. Pierre St. Amand of the Naval Weapons Center, China Lake, California, was provisionally designated WMU-2(XCL-1)/B.

The new unit is fired from the same type of rack and cartridge case as is the STORMFURY I round. Its pyrotechnic grain is also similar in composition and performance to that of the earlier unit, but it incorporates pressure relief, bore-safety, and time delay functions that will permit it to be certified for general use in all appropriate racks and aircraft without special supervision.

More details of the pyrotechnics used can be found in Appendix D of the 1969 Project STORMFURY Annual Report.

AREAS OF OPERATIONS

Eligible areas for experimentation in 1970 were the Gulf of Mexico, the Caribbean Sea, and the southwestern North Atlantic region.

Operations in these areas were limited by the following guideline: A tropical cyclone was considered eligible for seeding as long as there was only a small probability (10 percent or less) of the hurricane center coming within 50 miles of a populated land area within 18 hours after seeding.

There are two primary reasons for not seeding a storm near land. First, a storm seeded further at sea will have reverted to its natural state prior to affecting a land area Second, large changes in the hurricane structure occur when it passes over land. These land-induced modifications would obscure the short period effects expected to be produced by the seeding experiments and greatly complicate the scientific evaluation of the results.

PLANS FOR FIELD OPERATIONS - 1970

The period 20 July to 31 October was established for STORMFURY operations in 1970. The following aircraft were planned as STORMFURY forces during the season:

1. Navy Weather Reconnaissance Squadron Four
   Four WC-121N's
2. Marine All-Weather Attack Squadron Two Two Four
   Four A-6 Intruders

3. NOAA Research Flight Facility
   Two DC-6's
   One B-57
   One C-54 (replaced by a C-130 during the season)
4. Air Force 53rd Weather Reconnaissance Squadron
   Two WC-130's
5. Air Force 55th Weather Reconnaissance Squadron
   One WC-135
6. Air Force 58th Weather Reconnaissance Squadron
   One RB-57F
7. Naval Air Test Center
   One P3
8. Naval Weapons Center
   One Cessna 401.

Operations Plan No. 1-70 was provided to participants. It covered flight operations, communications, instrument calibration and use, data collection and distribution, logistic and administrative procedures, airspace reservations agreements, and public affairs.

The plan also provided for a series of fall-back research missions to be used when no eligible hurricane was available for seeding after deployment of project forces. These research missions are primarily data gathering or storm monitoring missions in unseeded cloud systems or storms.

As recommended by the STORMFURY Advisory Panel, first priority was given to the eyewall experiment in order to gain additional data which could be correlated with those collected during the 1969 "Debbie" seeding experiments.

This multiple seeding of the clouds in the annulus radially outward from the maximum hurricane winds calls for five seedings at 2-hour intervals. Each seeding consists of dropping 208 pyrotechnic units along a radially outward flight path, starting just outside the radius of maximum winds. The hypothesis in 1969 and early 1970 stated that the introduction of freezing nuclei (silver iodide crystals produced by the pyrotechnics) into the clouds in and around the eyewall should cause a chain of events that includes the release of latent heat, warming of the air outside the central core, changes in temperature and pressure gradients, and a reduction in maximum winds. Data from several experiments and individual cases are needed before definite conclusions regarding the validity of this hypotehsis can be assumed.

Because the magnitude of natural variations in hurricanes is sometimes as large as the hypothesized artificially induced changes, it is frequently difficult to distinguish between the two.

Second priority was given to the rainsector and third to the rainband experiments. The rainsector experiment is designed to test whether some of the latent energy in the air flowing toward the center of the hurricane can be intercepted and released while it is still between 50 and 100 miles from the center. If successful, this experiment should result in the dispersal of the energy over a larger area rather than concentration near the center. Clouds in a 45-degree sector between 50 and 75 miles radius are seeded to stimulate growth. This sector is selected because it is an area where an abundance of warm moist tropical air is being carried by the low-level winds toward the clouds nearer the center of the storm. If cloud growth in this sector causes moist air to ascend to the outflow layer at a relatively large radius, some of the energy normally released near the center of the storm would be released at greater radius and could result in a reduction in the storms' wind maxima.

All suitable clouds in the designated sector are seeded while monitoring aircraft continue to collect data to document changes in storm structure or intensity. The seedings are made in four periods of 50 minutes each, separated by non-seeding periods of 50 minutes.

The Rainband Experiment has the same objectives as does the Rainsector Experiment and, in addition, should permit the opportunity to study the interaction of seeded clouds with other clouds in the same and nearby rainbands. Clouds are seeded along a rainband (a line of clouds spiraling around and toward the center of the storm) at 50 to 150 miles from the storm center. Seeding of such a rainband may produce a dispersion of the energy of the hurricane over a larger area and should provide information and data needed to improve the design of other modification experiments. The rainband experiment provides data needed for studies of cloud interactions. A rainband can be selected that is well removed from the central vortex area and not obscured by the main cloud system of the hurricane. This selection facilitates visual observations.

The Advisory Panel has recommended that cloudline experiments continue to be conducted in order to collect data vital to the understanding of the dynamics of clouds organized into systems such as rainbands. These experiments can be conducted when there are no hurricanes and should provide additional opportunities for evaluation of seeding effects. During these experiments, tests of various seeding agents and dispersing techniques can also be conducted. Cloudline experiments were scheduled for 24-31 July 1970, in the military operational areas near Puerto Rico.

Project STORMFURY field experiments are extremely complex operations that require extensive planning and effective coordination. During the multiple seeding experiments, there are as many as 12 aircraft simultaneously operating in the hurricane circulation. Safety of the aircraft and personnel is paramount throughout the experiment. It is obvious that training, professionalism, and dedication are vital to safe and successful operations in the weather extremes encountered. Radars, cameras, radios, and data collection systems must be in peak operating condition. The seeder aircraft must be carefully and accurately vectored by radar and voice communications for the seeding runs. Teamwork is mandatory. For these reasons, it is also imperative that dry-run exercises be conducted prior to operations in a hurricane environment. This dry-run also provides opportunities for testing equipment and procedures, and for crew training.

FIELD OPERATIONS

Dry-runs were conducted from the Naval Station Roosevelt Roads, Puerto Rico, on 21 and 23 July, following a general briefing on 20 July. Participating in the dry-runs were aircraft from the Navy Weather Reconnaissance Squadron FOUR (VW-4), NAS Jacksonville, Florida; NOAA's Research Flight Facility, Miami, Florida; Marine All-Weather Attack Squadron Two Two Four (VMA-AW-224), MCAS Cherry Point, North Carolina; Air Force 53rd Weather Reconnaissance Squadron, Ramey AFB, Puerto Rico; and the 55th Weather Reconnaissance Squadron, McClellan AFB, Sacramento, California.

Also taking part were scientists from the Naval Weather Service Command Headquarters, Washington, D.C.; Naval Weapons Center, China Lake, California; Fleet Weather Facility, Jacksonville, Florida; Navy Weather Research Facility, Norfolk, Virginia; University of Miami, Coral Gables, Florida; and NOAA's National Hurricane Research Laboratory, Coral Gables, Florida.

Dry-run exercises for the STORMFURY eyewall experiment were conducted on 21 July and for the rainsector/rainband experiment on 23 July. Extensive individual debriefs of each flight were made followed by a general critique covering the total operations after each experiment.

A series of cloudline type experiments were carried out at the conclusion of the dry-runs with a portion of the forces. (The Marine A-6 aircraft, the Air Force WC-135, and two of the Navy WC-121N's were released.) Flight operations were carried out on 24, 27, 28, 29, 30, and 31 July, utilizing three types of seeding aircraft (Cessna 401, DC-6, B-57). See appendix I for report on the Cessna 401 operations.

The DC-6 was used on the last three operating days to seed with various silver iodide compositions generated from a burner attached to the wing. A report on these operations is included as appendix E.

On 19 August, Tropical Storm Dorothy developed east of the Caribbean Sea and was predicted to move into the Caribbean on the 20th. In anticipation that the storm would either intensify into a hurricane or remain stable enough in intensity as a tropical storm to serve as a fit subject for a STORMFURY monitoring mission, the forces (with the exception of seeder aircraft) were requested to deploy to Puerto Rico on 20 August. The monitoring mission was to include the flight patterns used to monitor a seeded hurricane. These data collected in an unseeded storm were to be used for comparison purposes and for research on the natural variability of storms.

The Research Flight Facility flew a three-plane mission of the monitoring type on 21 August, and the other project aircraft (less seeders) arrived for the major effort on Saturday, 22 August.

After crossing Martinique, Dorothy started weakening slowly. On Friday, the 21st, there was still a closed circulation, but the Research Flight Facility aircraft had difficulty orienting their flight patterns about the broad weak center. By Saturday, the 22nd, the storm had reverted to a tropical wave with maximum winds of about 45 knots. The STORMFURY monitoring mission was then changed to a fall-back research flight mission which collects data at several levels on a tropical wave. These data should prove to be very valuable for studying the structure of easterly waves, for data of this type have been extremely rare in the past.

Forces performed in an outstanding manner throughout the dry-run exercises, the cloudline experiments, and the Tropical Storm Dorothy operations. The fall-back exercise gave the first opportunity to work with all three of the Air Force participants (WC-130, WC-135, RB57F). Several problems were found in data collection and were resolved as a result of experience gained during these operations.

RESEARCH ACTIVITIES

Progress in the hurricane modification work was quite considerable in 1970 even though nature did not provide a suitable hurricane for a field experiment. This progress was due to the efforts of the research workers, and their findings provide a much broader and firmer base for the future work of the Project. This research took place primarily at the National Hurricane Research Laboratory, Coral Gables, Florida; the Navy Weather Research Facility, Norfolk, Virginia; and at cooperating Universities. Appendices B through L are reports on some of these STORMFURY research efforts.

Appendix B "A hypothesis for modification of hurricanes," by Drs. R. C. Gentry and H. F. Hawkins, explains the new hypothesis on hurricane modification experiments that was developed this year. The article summarizes the evolution of ideas concerning the use of freezing nuclei for modifying hurricanes, explains how the new hypothesis accounts for the apparently favorable results from the experiments on Hurricanes Esther (1961), Beulah (1963). and Debbie (1969), and discusses some of the questions concerning hurricane modification which still need to be answered either by the theoretical investigations or by the field experiments.

Appendix C "Hurricane modeling at the National Hurricane Research Laboratory, 1970," by Dr. S. L. Rosenthal, reviews the NHRL's more significant achievements in the general area of time-dependent hurricane modeling. Dr. Rosenthal discusses the specific problem of modeling a Debbie-like field experiment and summarizes efforts less directly related to the development of time-dependent models. He also outlines investigations planned by this group for the next few years.

Appendix D "Summary of the preliminary results from an asymmetric model of the tropical cyclone," by Dr. R. A. Anthes, Dr. S. L. Rosenthal, and J. W. Trout, shows that the asymmetrical hurricane model reproduces many observed features of the three-dimensional tropical cyclone. Realistic portrayals of

spiral rainbands and the strongly asymmetric structure of the outflow layer are obtained. The kinetic energy budget of the model compares favorably with empirical estimates and also shows the loss of kinetic energy by truncation errors to be very small. Large-scale horizontal asymmetries in the outflow are found to play a significant role in the radial transport of vorticity during the mature stage and are of the same magnitude as the transport by the mean circulation. In agreement with empirical studies, the outflow layer of the model storm shows substantial areas of negative absolute vorticity and anomalous winds.

Appendix E "Response of STORMFURY cloudline cumuli to AgI and AgI·NaI ice nuclei from a solution-combustion generator," by E. E. Hindman, II., Dr. S. D. Elliott, Jr., Dr. W. G. Finnegan, and B. T. Patton, studies the responses of cumulus clouds to silver iodide seedings during the 1970 STORMFURY cloudline operations and compares the effectiveness of two different silver iodide solutions burned in a solution-combustion generator.

Appendix F "Measurements of vertical motion in the eyewall cloud region of Hurricane Debbie," by Dr. T. N. Carlson discusses the estimates of cumulus cloud vertical motions recorded by an RFF DC-6 aircraft while flying in Hurricane Debbie. The accuracy of the vertical motions obtained is discussed, and various factors which may affect the accuracy are explained.

Appendix G "An estimate of the fraction ice in tropical storms," by Dr. W. D. Scott and C. K. Dossett, presents estimates of fraction ice in tropical storms collected in Tropical Storm Inga and Tropical Depression No. 14 as obtained through the use of the foil impactor and formvar replicator.

Appendix H "Ice phase modification potential of cumulus clouds in hurricanes," by D. A. Matthews, presents an examination of ice-phase modification potential of cumulus clouds. Predicted results of modification potential by a one-dimensional steady-state cumulus model are used to test the suggestion (Gentry, 1971) that an important effect on hurricanes may be realized by seeding the less fully developed cumulus cells that are located slightly outward from the mammoth clouds in the inner eyewall. Mr. Matthews's paper also describes the decreases in surface pressure, the increases in rainfall, and the increases in cloud top height as derived from model simulation of the ice-phase modification. In the calculations, he uses 87 temperature soundings observed within 100 n miles of hurricane eyes and five average hurricane soundings prepared by Sheets (1969).

Appendix I "Use of light aircraft in STORMFURY activities," by Dr. S. D. Elliott, Jr., and Dr. W. G. Finnegan, describes the use of contractor-operated light aircraft in Project STORMFURY dry-run and cloudline experiments and offers conclusions and recommendations involving the use of light aircraft in future STORMFURY activities.

Appendix J "Use of echo velocities to evaluate hurricane modification experiments," by P. G. Black, examines radar echo velocities computed over the entire storm for six time intervals before and during the seeding of Hurricane Debbie on 20 August 1969. He finds that mean echo speeds equaled or exceeded cyclostrophic winds computed from 12,000-ft D-value data as well as measured 12,000-ft winds after a correction for water motion was applied to the original "Doppler winds." Mr. Black further examines mean echo crossing angles to determine their variations and angular rotation in relation to the storm's major and minor axes.

Appendix K "A summary of radar precipitation echo heights in hurricanes," by H. V. Senn, surveys radar height data and hurricane case histories to determine likely occurrence of clouds that can be significantly modified in various sectors of a hurricane. This information suggests that clouds exist in hurricanes of the type that the new hypothesis (app. B) suggests are needed in the hurricane modification work.

Appendix L "Project STORMFURY experimental eligibility in the Western North Pacific," by W. D. Mallinger, updates and reviews numbers of typhoons eligible for Pacific STORMFURY experiments. This study strongly indicates that both Guam and Okinawa must be available as bases for Project forces in order to expect a profitable number of experimental storms during a 3-month operation.

OPERATIONAL AND RESEARCH DATA COLLECTION

Data collection procedures appeared adequate for the Project. While problems with radar still existed on some of the Project aircraft, continuous efforts were made during the season to improve these observational tools.

Two special Polaroid cameras (CU-5) were purchased and modified for use on the Air Force WC-130 aircraft radar. Although automatic time-lapse radar cameras are preferred, the Polaroid cameras produced good research data where none had been previously available from these aircraft.

The Research Flight Facility conducted several research missions in tropical circulations, but the 1970 hurricane season was generally one in which few good data collection opportunities occurred.

A one-plane mission was flown into Hurricane Ella in the far southwest Gulf of Mexico on 11 September.

A three-plane, five-level mission was flown into Tropical Storm Felice on 15 September. Felice was almost up to minimal hurricane force, and wind gusts as high as 64 knots were noted as it passed to the south of the Mississippi Delta region.

A three-plane, five-level mission on 2 October and a two-plane mission on 3 October were flown in Tropical Depression No. 14 as it passed through the eastern Caribbean.

Processing of STORMFURY films was again accomplished at a commercial firm in Miami. Some experiments in reducing costs by obtaining work prints to satisfy requirements for duplicates were attempted, but technical difficulties in processing were encountered. These difficulties are now believed to be surmounted, and a modified version of this procedure will be tried during the 1971 STORMFURY season.

OUTLOOK FOR 1971

Project STORMFURY operations are expected to be very similar to those planned for 1970. It is likely that the dry-run exercises will be conducted from the Naval Station Roosevelt Roads, Puerto Rico, followed by a series of cloudline experiments with forces based at Barbados.

Continued emphasis will be placed on repeating the "Debbie" type experiment and conducting monitoring missions in unseeded storms for comparisons purposes.

Project aircraft will be essentially the same as in 1970, except that a WP-3 weather reconnaissance aircraft belonging to Navy Weather Reconnaissance Squadron FOUR (VW-4) is expected to participate in STORMFURY missions for data collection and for additional use and evaluation as a seeder aircraft.

REFERENCES AND SPECIAL REPORTS

Anthes, R. A., S. L. Rosenthal, and J. W. Trout (1970): Numerical simulation of a hurricane. *Proceedings of the Meteorological Technical Exchange Conference*, 21-24 September, Annapolis, Md., U.S. Naval Weather Service Command.

Anthes, R. A. (1971): The response of a 3-level axisymmetric hurricane model to aritificial redistribution of convective heat release. Technical Memorandum ERLTM-NHRL, No. 92, NOAA, Dept. of Commerce, NHRL, Miami.

Black, P. G., and T. T. Fujita (1970): In- and outflow field of Hurricane Debbie as revealed by echo and cloud velocities from airborne radar and ATS-III pictures. *Proceedings of the 14th Annual Conference on Radar Meteorology*, Tucson, Ariz. November, pp. 353-358.

Black, P. G., H. V. Senn, and C. L. Courtright (1971): Some airborne radar observations of precipitation tilt, bright band distributior, and eye configuration changes during the 1969 multiple seeding experiments in Hurricane Debbie. Submitted for publication in the *Monthly Weather Review*.

Carlson, T. N., and R. C. Sheets (19 1): Comparison of draft scale vertical velocities computed from gust probe and conventional data collected by a DC-6 aircraft. Technical Memorandum ERLTM-NHRL No. 91, NOAA, U.S. Dept. of Commerce, NHRL, Miami, Fla.

Gentry, R. C. (1970): Progress on hurricane modification research - October 1969 to October 1970. Presented at the *Twelfth Interagency Conference on Weather Modification*, October 28-30, Virginia Beach, Va.

Gentry, R. C. (1970): Hurricane modification - Experiments and prospects. Presented at *Hurricane Foresight Conference*, New Orleans, La., April 30, and distributed by the New Orleans States-Item.

Gentry, R. C. (1970): Modification experiments on Hurricane Debbie, August 1969. *Proceedings of the Second National Conference on Weather Modification*, American Meteorological Society, pp. 205-208.

Gentry, R. C. (1970): The hurricane modification project: Past results and future prospects. *Proceedings of the Seventh Space Congress*, April 22-24, Cocoa Beach, Fla.

Gentry, R. C. (1970): Modifying the great storm on earth -- the hurricane. *Underwater Science and Technology Journal,* December, pp. 204-214.

Gentry, R. C. (1971): To tame a hurricane. *Science Journal, 7,* (1), January, pp. 49-55.

Gentry, R. C. (1971): Hurricane. *McGraw-Hill Yearbook of Science and Technology,* pp. 232-234.

Hawkins, H. F. (1971): Modifying the hurricane. Submitted for publication in *UMSCHAU* (German publication), April.

Hawkins, H. F. (1971): Comparison of results of the Hurricane Debbie (1969) modification experiments with those from Rosenthal's numerical model simulation experiments. *Monthly Weather Review, 99,* (5), May, pp. 427-434.

Mallinger, W. D. (1970): Project STORMFURY operations and plans. *Mariners Weather Log, 14,* (5), September, pp. 262-266.

Underwood, L. J. (1970): Project STORMFURY operations 1970. Presented at the *Twelfth Interagency Conference on Weather Modification,* October 28-30, Virginia Beach, Va.

APPENDIX A

REPORT ON MEETING OF PROJECT STORMFURY ADVISORY PANEL

Miami, Florida

29-30 September 1970

INTRODUCTION

In response to the recognition of the increasing importance of computer simulation of both "natural" and "seeded" hurricanes to the interpretation and design of Project STORMFURY field experiments, the Advisory Panel met at NHRL on 29-30 September to undertake a more intensive evaluation of models developed by Rosenthal and colleagues at NHRL. From this assessment, several conclusions and recommendations emerged.

EVALUATION OF HURRICANE MODELING

Results of computer simulations of natural hurricanes were available from two models: the improved symmetric (two-dimensional) model with explicit water cycle and air-sea energy exchanges and better horizontal resolution of 10 km, as well as preliminary results from a simplified asymmetrical (three-dimensional) model which neglects interaction with the environment, has constant Coriolis parameter, and rather coarse vertical and horizontal resolution. Simulation of seeded hurricanes was carried out solely with the use of the symmetrical model. Varying augmented heating rates were applied at different radial increments both continuously and intermittently for 10 hours in an attempt to simulate the multiple eyewall experiment of Project STORMFURY.

From a study of these results the Panel reached the following conclusions:

(1) Within the limitations imposed by symmetry and convective parameterization, the simulation of the natural hurricane is impressively realistic. The distributions of temperature, pressure, and horizontal and vertical motion of the model storm compare favorable with those observed in typical mature hurricanes in nature.

(2) Within the limitations of the simple asymmetrical model given above, plus the recognition that some asymmetry is introduced artificially by round-off errors and boundary geometry, an asymmetrical structure develops in a manner and with a structure that is not unrealistic. When averaged in the azimuthal direction, the structure is sufficiently similar to the symmetrical analog to give increased confidence in the validity of the symmetrical model. The favorable comparison of model storm structures with observation lends credence to the simulation of seeded hurricane structure. In spite of the realistic simulation of hurricane structure, the Panel noted that neither the symmetrical nor the asymmetrical model is able to give any information on the effects of internal or external influences on the motion of natural or seeded hurricanes.

(3) The essential result which emerges from the seeding simulation is the formation of a new wind maximum and zone of strongest upward motion at a greater radius than those existing in the natural model storm if the augmented heating rate is added *outside* these pre-existing maxima. Only minor differences in this essential result appear in experiments with different augmented heating rates at different radii.

(4) This new wind maximum which forms in the seeded storm is weaker than the model control by about 10 percent. Larger reductions of wind speed occur at the radius of maximum wind of the control storm and smaller increases occur at radii beyond the new maximum. The decreases in wind speed are associated with decreased horizontal temperature gradients in the upper and middle troposphere and weakened surface pressure gradients together with the fact that inflowing air rises at a greater radius, thus acquiring smaller tangential relative momentum. The augmented heating also increases the static stability which is associated with smaller rates of release of latent heat and conversion of available potential to kinetic energy.

(5) Evidence from available simulations has, so far, always indicated that seeding at radii outside the original wind maximum results in reduction of the maximum winds. However, the augmented heating associated with the simulated seeding results in an *increase* in the *total* kinetic energy of the hurricane winds by about 20 percent. Since this could result in a significant increase in the

storm surge, we caution against conclusions that seeding does not make the storm "worse." Furthermore, "simulated seeding" *inside* the original radius of maximum winds results in a slight *increase* of strongest winds.

(6) The augmented heating rates used to simulate seeding probably cannot be realized in nature solely from release of latent heat of fusion. The most reasonable analog in nature is the possibility that convective clouds in the region just outside the existing eyewall could be stimulated by seeding to more active growth and intensity thus replacing the previous eyewall with a new one at a greater radius. Augmented heating from enhanced condensation, plus freezing in such circumstances, probably exceeds the augmented heating rates used in the seeding simulations.

RECOMMENDATIONS

Based upon the above conclusions, the Advisory Panel makes the following recommendations with regard to Project STORMFURY:

Recommendation ONE: More detailed diagnostic studies of existing simulations of seeding should be carried out to verify the tentative conclusions reached above as to the mechinisms of the seeding influences. In particular, other quantities than those now available should be studied with greater time resolution.

Reasons: It is essential to understand the seeding simulations in as great detail as possible to gain confidence in the results and for comparison with field experimental results.

Recommendation TWO: Development of the asymmetrical (three-dimensional) model should be continued with the ultimate objective of modeling the nonstationary hurricane as it moves through and interacts with the larger scale environment. When this has been achieved for natural storms, simulation of seeding should be carried out.

Reasons: Only with such a model it is possible to investigate interactions between the hurricane and its environment and remove the constraint of axial symmetry. Furthermore, simulation of seeding in only one sector of the storm will be possible, as well as investigating the possible effects of seeding on the motion of hurricanes.

Recommendation THREE: Further simulations of seeding should be made with the symmetrical (two-dimensional) model to supplement the diagnostic studies of existing seeding simulations recommended above.

Reasons: Additional information on varying augmented heating rates and radii of seeding is needed. It is also anticipated that the diagnostic studies will reveal points in need of further clarification.

Recommendation FOUR: The resources of the computer simulation group under Dr. Rosenthal at NHRL should be augmented by: (a) two Ph.D. level scientists with appropriate qualifications, and (b) computer facilities of greater speed and capacity.

Reasons: Although excellent progress has been made by this group in the past 2 years, the experiments recommended above will require additional personnel and computer facilities to accelerate this rate of progress in the next 2 years.

Recommendation FIVE: Available radar data should be studied in an attempt to verify the existence of convective clouds just outside existing eyewalls with a structure susceptible to enhanced growth through seeding. Results from Hurricane Debbie should be reviewed once more from this point of view.

Reasons: If verified, the existence of such clouds and their enhancement by seeding would provide a sounder hypothesis for STORMFURY field experiments.

Recommendation SIX: Radar and cloud physics instrumentation on the research aircraft should be further improved to give more quantitative information on the distribution of convective and other clouds and all phases of water in the hurricane.

Reasons: The essence of possible modification of hurricanes rests in the questions of influencing the intensity and organization of convection and the associated phase changes of water. Unless more and better data can be acquired on these questions, residual doubt will always remain in the interpretation of experimental results.

Professor Noel E. LaSeur, Chairman
Dean Charles L. Hosler
Professor James E. McDonald
Professor Edward N. Lorenz
Professor Jerome Spar

10 November 1970

RECOMMENDATIONS OF THE ADVISORY PANEL FOR PROJECT STORMFURY

Washington, D.C.

February, 1971

INTRODUCTION

In the course of the meeting of the Advisory Panel for Project STORMFURY held in Washington, D.C., 28-30 January 1971, two aspects of Project activities emerged which need immediate action if necessary planning is to be accomplished. These are: the proposed operations of Project STORMFURY in the Pacific during the summer of 1972; and the acquisition, outfitting, and testing of alternate seeding aircraft. Because of the immediacy of these problems, the Advisory Panel is issuing these recommendations; further recommendations on other aspects of Project activities discussed will be forthcoming.

Recommendation ONE: The Panel recommends that appropriate agencies of the government intensify efforts to solve the financial, logistic, diplomatic, and other problems associated with proposed operations of Project STORMFURY in the typhoon region of the Western North Pacific Ocean during the summer of 1972.

Reasons: The increased opportunities for STORMFURY experiments to be expected from the typically greater frequency of Pacific typhoons in a large, sparsely populated oceanic region fully justify the expense and effort required to move Project operations to that area. There is every reason to believe that experimental results obtained in Pacific typhoons will be completely valid for Atlantic hurricanes.

Recommendation TWO: The Panel recommends that Project STORMFURY continue efforts to acquire, outfit, and test alternate seeding aircraft with the following capabilities: increased capacity to carry Project personnel and seeding pyrotechnics; increased range and time "on-station" in the storm; and capability to seed at levels in the range from 25,000 ft to 30,000 ft or at lower levels if suitable temperatures for seedings exist.

Reasons: The Panel considers it undesirable for the Project to have to rely on seeder aircraft from external units. In the past, available aircraft have lacked capacity for Project personnel to fly on-board, and thus provide better

control of the time and place of seeding. They have also lacked range, capability fcr mulitple seeding without refueling, and were limited to high altitudes. Acquisition by the Project of aircraft with the recommended capabilities could eliminate significant uncertainties inherent in the presently available planes.

Professor Noel E. LaSeur, Chairman
Dean Charles L. Hosler
Professor James E. McDonald
Professor Jerome Spar

APPENDIX B

A HYPOTHESIS FOR MODIFICATION OF HURRICANES

R. Cecil Gentry and Harry F. Hawkins
National Hurricane Research Laboratory

INTRODUCTION

The encouraging results from the Hurricane Debbie modification experiments of August, 1969 (Gentry, 1970a) have stimulated research on many problems related to hurricane modification experiments. One of the more interesting developments during 1970 was a new hypothesis which accounted for results from the "Debbie" experiments and offered a more acceptable rationale that details how seeding a hurricane can cause a reduction in its maximum intensity.

R. H. Simpson proposed in 1961 that hurricanes might be modified by introducing freezing nuclei into the massive cloud wall surrounding the center of a hurricane. His hypothesis was set forth in a number of papers (e.g., Simpson and Malkus, 1965; 1964b). It suggested that there was sufficient supercooled water (particularly in the "chimney" area) which, if suddenly frozen, would release enough latent heat of fusion to permit increasing the cloud temperatures 1 to 2°C. By assuming that there was an effective lid on top of the storm and using a hydrostatic model, he calculated that the maximum pressure gradient in the storm might be reduced by 10-15 percent if the heating effects could be confined to a selected area. He further hypothesized that this would be accompanied by a similar percentage reduction in the maximum winds.

In 1968, a hurricane model developed by S. L, Rosenthal was used for some preliminary experiments relative to the modification hypothesis (Gentry, 1969). In these experiments, seeding of the clouds was simulated by assuming that the seeding would result in enhanced heating of the seeded clouds sufficient to change the temperature at the rate of 2°C per ½ hour for ½ hour. That is, the seeding was *simulated* by increasing the heating function in a specified volume of the storm. In the model, heat was added at 500 mb and 300 mb, the levels where introduction of artificial freezing nuclei would most likely result in freezing of significant amounts of water. Calculations were then made with the model to

determine in which portion of the storm addition of heat would most likely result in reduction of the maximum winds; in an: (1) annular band radially inward from the maximum winds, (2) annular band spanning the radius of maximum winds, or (3) annular band radially outward from the radius of maximum winds. The answer from the model was that reductions were most likely when the heat was added radially outward from the maximum winds.

Based on these experiments with the model, crude as they were, the seeding pattern for the experiment was redesigned. Formerly, the seeding aircraft crossed the eye of the hurricane and started dropping the pyrotechnic silver iodide generators at the inner edge of the eyewall. The run continued radially outward for 15 to 25 miles (Simpson and Malkus, 1964a). Prior to the 1969 hurricane season, this pattern was altered to have the run start about 3 miles radially outward from the inner edge of the eyewall (past the ring of maximum winds) and continue on for 15-25 miles. This meant a relatively small change in the annular band seeded because there was about an 85 percent overlap in this pattern and the one used in the earlier seeding runs on hurricanes.

Debbie was seeded five times at 2-hour intervals on 18 August 1969, and again on 20 August (Gentry, 1970b). The operational plan called for the seeding runs to be from the radius of maximum wind outward for 15-25 miles (the spread was somewhat a function of the reaction time of the man in the seeder aircraft and the turbulence encountered). When operations are conducted, it is frequently difficult for the Project Director in the command-control aircraft to know the exact location of the radius of maximum winds, but he does have a good radar picture of the hurricane. R. Sheets, National Hurricane Research Laboratory, has studied the flight data collected by the Research Flight Facility and the National Hurricane Research Laboratory during the last 14 years, and has concluded that in mature hurricanes the most likely radius for the maximum winds was 2 or 3 miles radially outward from the inner edge of the eyewall (as seen by radar)[1].

By the time of the Debbie experiments, S. L. Rosenthal had made several improvements in the hurricane model. The encouraging results from the field experiments put much greater emphasis on all phases of the research effort, and a new series of experiments simulating the modification effects were made with the more sophisticated model (Rosenthal, 1970).

---

[1] Personal communication.

The new experiments also simulated the modification experiment by assuming that seeding would add heat to the clouds. It was again found that a reduction in maximum winds was most likely if the heat was added radially outward from the radius of maximum winds. Several variations were run in which changes were made in the intensity of the enhanced heating function, in the radial bands at which it was applied, and in the length of time of application. There were also experiments to consider whether the heating should be applied continuously or in pulses to simulate the multiple seeding experiments conducted on Debbie.

In general, the results showed that a reduction in maximum winds was most likely if the heat were added radially outward from the radius of maximum winds. They also showed that there was little difference in the reactions between heat added continuously and heat added in pulses. Larger amounts of enhanced heating caused quicker responses in the wind field, but eventually the reduction in maximum winds became about the same. There did seem to be a lower limit to the rate at which heat should be added below which no significant change in the maximum winds occurred within 10 to 20 hours (Rosenthal, 1971).

During the 1968, 1969, and 1970 seasons, the National Hurricane Research Laboratory with the assistance of the Research Flight Facility of NOAA made some measurements of the liquid- and solid-water content of hurricane clouds (Sheets, 1969).

These measurements were limited in number because of the infrequency of hurricanes within range of the aircraft bases and due to failure of measuring equipment. Nevertheless, some information became available on how much heat might be furnished hurricane clouds by introducing freezing nuclei. One tentative conclusion was that there was possibly enough supercooled water in the major eyewall clouds to furnish latent heat to change the temperature 1 or 2°C if all this liquid was frozen "simultaneously." There was considerable doubt about whether the average supercooled water content over the entire seeded band was sufficient to account for the heating rates suggested by Rosenthal's model runs through heat of fusion alone. On the other hand, it is extremely dangerous to transfer the quantitative aspects of model runs, whether in terms of heating rates, reaction times, or whatever, into direct experimental values. The runs should be used as qualitative guides only.

When the multiple seedings were considered, however, there appeared to be too little supercooled water for the latent heat of fusion to be an adequate sole heat source. Once the liquid in the clouds has been frozen, one cannot keep refreezing it to get more heat. Only by introducing fresh supercooled water into the clouds can one get the additional heat by this mechanism. Simple calculations suggest that heating rates through the release of latent heat of fusion would be 1 to 2 orders of magnitude less than the amount calculations with Rosenthal's hurricane model suggest is needed if one is to get significant reductions in the maximum winds within 4 to 10 hours. In further view of the fact that there appears to be a lower limit below which the heating has no apparent effect, this limited small heat source gave serious concern to the scientists involved.

A new hypothesis for the source of the enhanced heating has been developed. We have reviewed the seeding procedures used in the Hurricane Esther, 1969 (Simpson et al., 1963), Hurricane Beulah, 1963 (Simpson and Malkus, 1964a), and Hurricane Debbie, 1969 (Gentry, 1970a, b) experiments and believe that the changes observed in each of these storms may be accounted for much more reasonably by the new hypothesis than by the original hypothesis. It provides for an improved interpretation of the Debbie results without requiring any *drastic* revision of the seeding patterns used in the hurricane experiments. If this hypothesis is confirmed, however, it will permit changes in the seeding patterns and seeding altitudes to allow more efficient use of the Project aircraft that are likely to be available in future years.

A NEW SEEDING HYPOTHESIS

The new explanation reemphasizes that the seeding should be done radially outward beyond the tallest clouds in the eyewall and at radii greater than that of either the greatest ascending motion or the maximum winds. The first goal of the seeding with silver iodide crystals is to cause freezing of supercooled water droplets in towering cumulus with tops at temperatures of -5 to -20°C and to release the latent heat of fusion. In the old explanation, the latter was the main reaction expected. In the new explanation, it is the initiation of a bigger reaction, i.e., the trigger that sets off a chain reaction. The latent heat of fusion is expected to increase the buoyancy of the towers to cause greater growth of the ascending plumes in the clouds, and ultimately *to result in condensation or sublimation of extra water vapor* at the radii of the seeding. Either of the latter

two processes can release many times as much heat as would be released by merely freezing the supercooled water droplets in the clouds. The stimulation of cloud growth at these radii accomplishes two ends: it allows the clouds to grow vertically up into the outflow layer so that air "circulating through this duct" never penetrates to smaller radii, and at the same time it increases the heat release at the radii of seeding. Obviously, air which is thus diverted upward never spirals on into the eyewall and is therefore unable to contribute its heat and angular momentum to maintaining the old ring of maximum winds.

Thus, one purpose of seeding the clouds outside the old eyewall is to develop a "new eyewall" at a greater radius. If this is accomplished, and most of the air flowing inward ascends at a larger radius, lower maximum wind speeds should result simply from conservation of angular momentum. H. Sundqvist (1970), who has also developed a hurricane model, recently expressed this same idea when he wrote, "Regarding the radial distribution of heating by condensation, we can conclude that the farther from the centre the maximum is, the farther from the centre will the maximum radial wind occur. And from absolute angular momentum considerations it is clear that the earlier (coming from the outside) the inflow ceases the less will the tangential wind be."

A first reaction to this proposal may be, "Hurricane clouds already extend to great heights. How can one make them grow taller?" In the eyewall this may indeed be difficult, but in all other regions it may be quite practical. H. V. Senn (app. K) studied RHI (vertical profiles of radar targets) radar pictures of hurricanes. He found many echoes whose tops were between 20,000 and 30,000 ft. Such clouds occupied much of the outer portions of the hurricane, and there were many even within 5 n miles outward from the inner edge of the eyewall. His data show that more than 50 percent of the echoes within 30 n miles of the center have tops in this range. These data are not adequate support for any strong conclusions, but Senn found nothing to indicate that most echoes in the vital annular ring naturally grew to the top of the troposphere. Thus, current radar data suggest it is possible to make the cumuliform clouds grow sufficiently to cause extra condensation (sublimation) of water vapor in the region where the simulation experiment with the Rosenthal model indicates that application of the enhanced heating function results in the greatest reduction in maximum winds.

Scientists in the Naval Weapons Center at China Lake, California (St. Amand, 1970; Schleusener et al., 1970), the Experimental Meteorology Laboratory of NOAA (Simpson and Woodley, 1971), Pennsylvania State University (Davis, 1966;

Davis et al., 1968) and other groups have all shown conclusively that under certain conditions, cumulus clouds, including those in the tropics, can be made to grow both vertically and horizontally by seeding and in some cases can be made to grow explosively.

The cloud environment in a hurricane is different from the mean tropical atmosphere, but there are reasons for believing that clouds outside the eyewall in a hurricane also can be made to grow by seeding. R. Sheets (1969a) using the cloud model developed at the Experimental Meteorology Laboratory (Simpson and Wiggert, 1969) has made computations as to the seedability of hurricane clouds using the mean soundings he developed for different radii (surface pressure) in hurricanes. Using assumptions considered reasonable, he calculated that cumuliform clouds similar to those found beyond the eyewall of hurricanes might be expected to grow considerably more than 5000 additional feet after being seeded. D. A. Matthews obtained similar results using a different cloud model (app. H).

A radar picture showing a vertical slice through the left rear quadrant of Hurricane Debbie, 20 August 1969, is shown in figure B-1. This picture was taken by one of the Navy's APS-45 (3 cm) radars. It shows the eyewall and the fine scale structure of some of the rainbands. The echoes from this picture have been reproduced in the right side of figure B-2. Note that the eyewall, 40 n miles from the aircraft (A/C), extends to at least the top of the scope which is at 40,000 ft. The other echoes end below 20,000 ft. The difference cannot be explained by attenuation because the radar saw through these echoes to the eyewall. Other aircraft in the area reported clouds from near sea level to above 40,000 ft, so there must have been stratiform clouds between the radar echoes throughout the area represented by the picture except in the eye of the storm. The echoes in the pictures presumably are associated with clouds that have the stronger ascending currents and the greater liquid-water content.

The left side of figure B-2 illustrates the basic factors considered in simulating the modification experiment with Rosenthal's model (1970b). The enhanced heating function was such as to change the temperature at the rate of 4°C hour^{-1} and was applied at 300 mb and 500 mb. The temperatures do not actually change this much because the extra heat is rapidly dispersed to other portions of the storm. Considering the levels used in the model and interpolations between levels, this means that the enhanced heating affects the layer between 600 mb and 250 mb or a layer 350 mb thick.

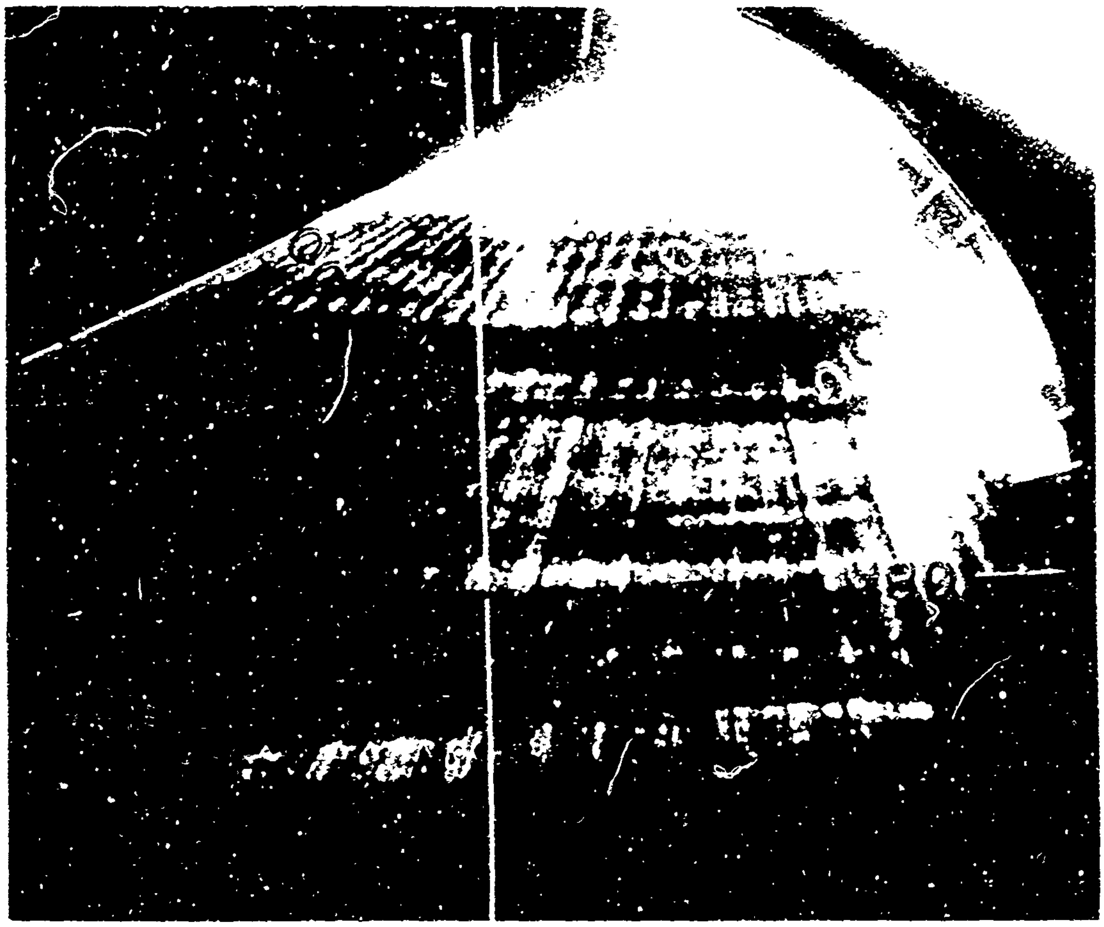


Figure B-1. Photo of the rainbands and southern eyewall of Hurricane Debbie, 20 August 1969, taken by the APS-45 (X-Band) radar operating in RHI mode on U.S. Navy Reconnaissance aircraft. The white line shows 20,000 ft elevation. The tallest echo (about 40 n miles from aircraft) is the eyewall.

Consider any vertical column 1 cm^2 in cross section and extending through a depth of 350 mb. Then the enhanced heating function calls for adding 0.0934 cal sec^{-1} to this column. In the reproduction of the radar band just to the right of the column (fig. B-2), some potential for growth is suggested. The specific humidity at the top of the radar echo was about 5.5 g kg^{-1} of air. If by seeding, one could initiate the release of latent heat of fusion and sufficient increase in cloud buoyancy to cause the ascending column to rise about 2000 additional feet, the specific humidity at the top would then be 4.5 g kg^{-1}. That is, 1 extra gram of water vapor would be sublimated or condensed and would release up to

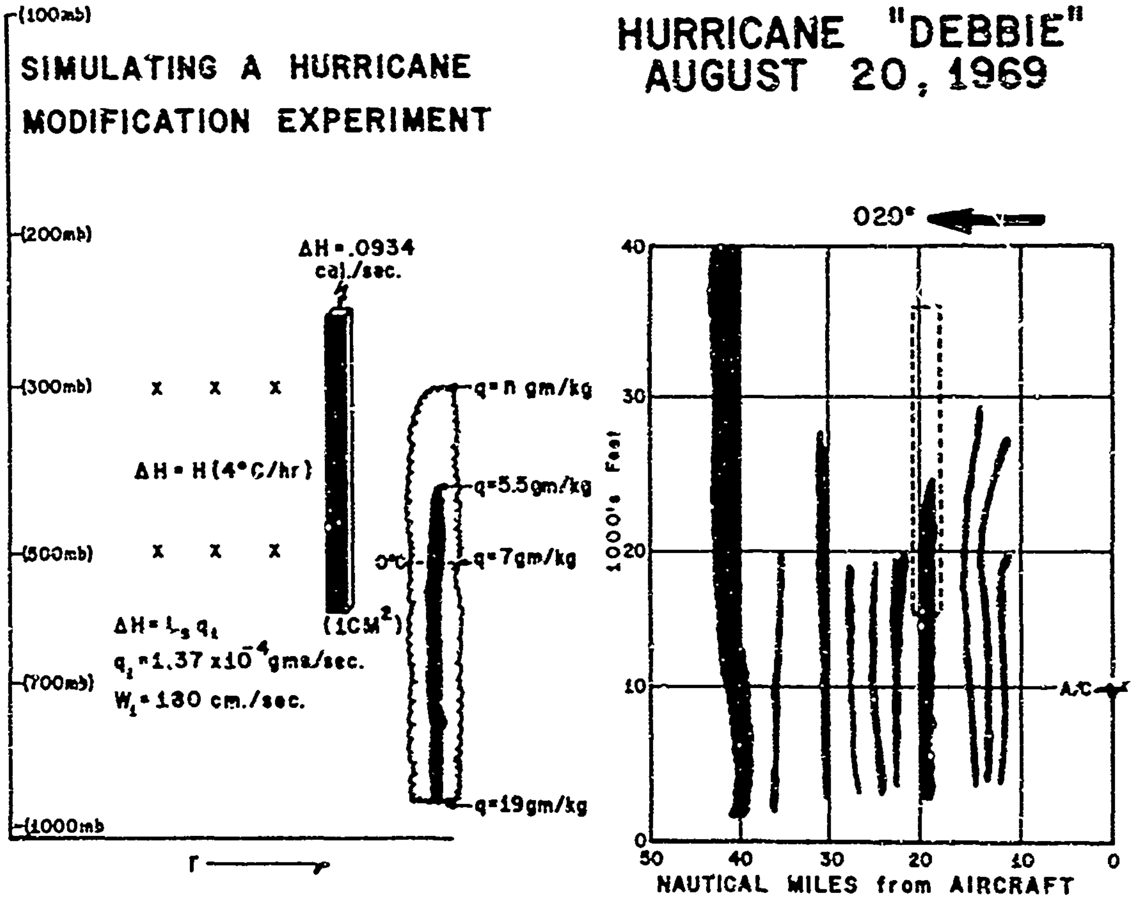


Figure B-2. Radar echoes from the original picture reproduced in Fig. 1 are in the right side of the diagram. The center of Hurricane Debbie was about 50 n miles north-northwest of the aircraft. The eyewall (40 n miles from aircraft) extended higher than 40,000 ft (limit of the radarscope). The left portion refers to calculations of amount of heat that can be released by seeding and to the amount of heat required for modification of a hurricane in the simulation experiment with a theoretical model (see text).

678 cal to warm the air column. We can make a rough check on whether this mechanism can furnish sufficient heat at the rate suggested by the calculations with the numerical models. If we assume that for each kilogram of air entering the base of the clouds, seeding causes 1 extra gram of water vapor to sublimate, we can calculate the vertical velocity needed to provide for the enhanced heating. For the entire annulus affected by the seeding an average vertical velocity of 180 cm sec^{-1} is needed at 600 mb to provide the required air flow. This is believed to be a conservative value based both on results from the modeling experiments and measurements

made of the divergence fields in hurricanes. Obviously updrafts will be stronger in the clouds in order for the average vertical velocity to be 180 cm sec^{-1}. Since we do not have accurate estimates of the percentage of the area that is covered by the active convective towers, we cannot state precisely what the average updraft speeds will be, but order of magnitude type calculations again suggest values that are in line with observations. Thus, it seems reasonable that the amount of heat required under the assumption of an enhanced heating function sufficient to cause temperature change at rates of 4°C $hour^{-1}$ can be provided by the latent heat of sublimation (or condensation) if the seeding will cause the clouds to grow an additional few thousand feet.

The U.S. Air Force Air Weather Service will make special efforts in 1971 to release dropsondes at radii outside the eyewall of tropical cyclones to provide data needed to make more reliable computations of the seedability (difference in height of seeded cloud and expected natural growth of the same cloud) of hurricane clouds outside the eyewall.

Qualitative support is provided by Rosenthal's modeling results to the idea that adding heat above the freezing level and outside the eyewall can cause a new eyewall to develop at a greater radius. In part of the volume in the model where the enhanced heating was applied, "natural factors" started operating and 13 times as much heat was released in the model computations as was added due to the artificial enhancement of the heating function. For the volume as a whole, the natural enhancement as represented by the increases in enthalphy was approximately 10 times as great as that added by the enhanced heating function (Rosenthal, 1971). This is further evidence that there is a latent instability present which can be triggered by properly applied heating.

The increased "natural" heating in the model is explained by what happened to the vertical motion in the "modified" model hurricane. Initially, the maximum updraft velocities were located between the 15 and 25 km radii. After the enhanced heating was applied between radii of 25-45 km, a new maxima of vertical motion developed there, and within less than 10 hours, the original maxima had disappeared. The shift to the radii of enhanced heating resulted in much greater condensation at those radii. Since the total volume of the annulus increases when its radii increases, the same vertical velocity results in a larger total rainfall for the modified storm. A detailed analysis of the vertical motion fields revealed two maxima for a short period, one at the radius of the original maximum, and the other at the radii

of the enhanced heating function. Eventually the latter became the larger, and a new eyewall (or at least the maximum vertical velocity) developed at the greater radii. Once the inflowing air at the low levels started ascending at the larger radii, the calculations with the model indicated a reduction in maximum winds. Winds at the new maximum wind radius were stronger than the old winds at that radius but less than the old maximum winds.

Examination of the seeding runs made in the various hurricanes that have been seeded, that is, Esther (1961), Beulah (1963), and Debbie (1969), reveals they were all seeded in [illegible] the same radial band or annulus. In the earlier cases, the seeding run started at the inner edge of the eyewall and in Debbie started at a point about 3 n miles radially outward from the inner edge of the eyewall. All seeding runs extended radially outward 14 to 30 n miles and most extended about 20 n miles. The new hypothesis suggests that the seeding run should start at a point about 5 n miles radially outward from the inner edge of the eyewall and go outward for 15 to 30 n miles. This constitutes an even smaller change in the radii from those used in the Debbie experiment than the changes from the seeding radii used for the 1961 and 1963 experiments to those of the Debbie experiment.

The present plans for the seeding and those used in the Debbie experiment call for the pyrotechnics to produce a curtain of silver iodide crystals from about 33,000 ft down to the freezing level. If the new hypothesis is correct, the seeding might be equally effective if the silver iodide generators produced the crystals from some lower level, for example, 27,000 ft, down to the freezing level.

QUESTIONS NEEDING BETTER ANSWERS

While the new hypothesis does suggest better answers to some of the questions that have been asked by critics of the hurricane modification experiments, there are still several questions which have not been adequately answered. A few of these are discussed in the following paragraphs:

(1) The basic question, of course, is, will the modification experiment work and, if so, under what conditions? Thus far we have been seeking answers to this question from the modeling experiments with back-up from information derived from the Hurricane Debbie experiments. While the latest version of the hurricane model does simulate many

features of hurricanes very well (Rosenthal, 1970), its developer says it is still in some respects a rather crude model. It should not be depended upon for final, authoritative, and quantitative answers about what results to expect from a modification experiment on an actual hurricane. More experience with this and more sophisticated models is needed.

(2) How do we get the freezing nuclei into the clouds where they are most likely to produce results? There are two problems here. The first involves getting the seeder airplane to the right position to put freezing nuclei into the clouds. While pilots are very experienced in flying aircraft through hurricanes, it is difficult for them to identify and fly to the portion of the cloud having the strongest updraft and to drop the silver iodide without encountering hazardous flight conditions. The second question is what happens to the silver iodide freezing nuclei that are released in a cloud without an ascending current. Presumably, they are swept around the storm by the winds. Are they entrained into the next updraft that they pass or do they skirt around it? Senn et al. (1971) and Hawkins and Rubsam (1968) have presented data about the radar bright band which suggest that there are already many naturally created ice crystals in the hurricane clouds outside of the active updrafts. If so, the artificial freezing nuclei that do not get into the updrafts initially may be mixed with the natural ice crystals and have little influence on later developments.

(3) The most difficult question we have had to answer in the Debbie and earlier experiments is how to evaluate the results. It is comparatively simple to determine whether the storm weakens or intensifies. It is difficult to learn whether the seeding caused the change or whether the change was a result of natural forces. The new explanation for why the seeding should work offers opportunities, however, for answering this question. We have a sequence of events which should occur: (a) There are convective clouds present which contain supercooled water and relatively few natural freezing nuclei. (b) These clouds do not extend to the top of the hurricane. (c) Seeding these clouds with silver iodide causes them to grow. (d) When the clouds grow, the temperature increases slightly in the area of the seeding. (e) A new eyewall starts to develop in that area. The radar on aircraft currently assigned to the Project can be used to monitor the clouds and record changes in the clouds in the seeded band for several hours to see if they grow at proper times and at rates expected to result from the seeding. If changes occur in conformance with the hypothesis, this would be very convincing evidence that the seeding contributed to these changes and to simultaneous changes in the wind speed.

(4) Where does water vapor come from that is condensed (or sublimated) to provide the heat required in the new hypothesis? In the simulation experiment made with the Rosenthal model, it was assumed that the enhanced heat came from releasing the latent heat of fusion from water already in the volume. In the new version of the hypothesis, we must account for new supplies of water vapor being condensed in greater quantities at greater radii, and this vapor must come either from the ocean, the low atmospheric levels, or from some mid-level portion of the storm. Anthes (1971) has investigated this problem and concluded that the reduction in the maximum winds that the model suggests will take place varies greatly depending on the origin of the water vapor that goes into the growing seeded clouds. S. L. Rosenthal discusses in appendix C, another method of simulating the seeding in the modeling experiments. Perhaps these new experiments he is planning will answer this question. In any case, this is a problem that will require much more research on both the hurricane and cloud scales of motion and their interactions.

(5) As has already been mentioned, there is a need to know more about the seedability of hurricane clouds. That is, can they be made to grow taller and larger by seeding? How numerous are they, how high should they grow, what volumes of low-level air might they divert?

FUTURE PLANS

The Air Weather Service (USAF) has already issued instructions to the hurricane hunter squadrons in the Atlantic and Pacific to make special efforts to get dropsonde data from the 300-mb level in tropical cyclones in the annulus, 5 to 40 miles radially outward from the inner edge of the eyewall. These data will make possible more definitive computations of the seedability of the hurricane clouds.

The Navy, NOAA, and Air Force aircraft will make extra efforts to get consistent radar coverage not only of experimental hurricanes, but also of nonexperimental hurricanes. The latter data will be used for establishing a range of natural variability that can be compared with the changes occurring in experimental hurricanes following seedings. The Navy aircraft have radar especially well-designed for this task. The radar data should also provide more information about the number and location of clouds that have seedability.

The Research Flight Facility and the National Hurricane Research Laboratory will continue their efforts to get more information about the amount and distribution of the liquid- and solid-water contents of the hurricane clouds.

As outlined in appendix C, greatly increased efforts will be devoted to improving the theoretical models of hurricanes.

Finally, every effort will be made to conduct additional modification experiments on hurricanes. These are necessary. No matter how the theoretical models are improved, and no matter how much cloud physics, radar, and other data are accumulated, they in themselves will be insufficient (for the foreseeable future) to determine whether we can modify hurricanes. The final answer will have to come from experiments on real storms.

ACKNOWLEDGEMENTS

Many people have contributed to the development of the new hypothesis. Some of these have been referenced in this paper. The first presentation of a preliminary version of the new hypothesis was made by the senior author at a meeting of the STORMFURY Advisory Panel on 29 September 1970. Many improvements in the hypothesis were suggested at that time. Among those participating were Professor Noel E. LaSeur, Professor Charles Mosler, Professor Edward Lorenz, Professor James E. McDonald, Professor Jerome Spar, Dr. Stanley Rosenthal, Dr. Harry F. Hawkins, Dr. Richard Anthes, Mr. William Mallinger, Mr. Peter Black, and Dr. William Cotton.

This presentation of the hypothesis is the work of the writers and any deficiencies should be attributed to them. If, however, the hypothesis proves to have great merit, credits should be shared with the ones listed above and the many people whose research has been referenced herein.

In addition, credit should be given to the scientists and technicians of the National Hurricane Research Laboratory (NOAA), Research Flight Facility (NOAA), Navy Weather Research Facility, and the Navy and Air Force Hurricane Hunter Squadrons who collected, processed, and analyzed the data needed to support the new ideas.

REFERENCES

Anthes, R. A. (1971): The response of a 3-level axisymmetric hurricane model to artificial redistribution of convective heat release. Technical Memorandum ERLTM-NHRL No. 92, NOAA, Dept. of Commerce, NHRL, Miami, Fla.

Davis, L. G. (1966): Alternation of buoyancy in cumuli. Ph.D. Thesis, The Pennsylvania State University, University Park, Penn.

Davis, L. G., J. I. Kelley, A. Weinstein, and H. Nicholson (1968): Weather modification experiments in Arizona. NSF Report 12A and Final Report NSF GA-777, Department of Meteorology, The Pennsylvania State University, University Park, Penn. 129 pp.

Gentry, R. C. (1969): Project STORMFURY. *AMS Bulletin, 50,* (6), June, pp. 404-409.

Gentry, R. C. (1970a): Hurricane Debbie modification experiments, August, 1969. *Science, 168,* pp. 473-475.

Gentry, R. C. (1970b): The hurricane modification project: Past results and future prospects. *Project STORMFURY Annual Report 1969*, U.S. Department of Navy and U.S. Department of Commerce, Appendix B.

Rosenthal, S. L. (1970a): A circularly symmetric primitive equation model of tropical cyclone development containing an explicit water vapor cycle. *Monthly Weather Review, 98,* (9) September, pp. 643-663.

Rosenthal, S. L. (1970b): A circularly symmetric, primitive equation model of tropical cyclones and its response to artificial enhancement of the convective heating functions. *Monthly Weather Review, 99,* (5), May, pp. 414-426.

Schleusener, R. A., P. St. Amand, W. Sand, and J. A. Donnan (1970): Pyrotechnic production of nucleants for cloud modification. *Journal of Weather Modification, 2,* (4), May, pp. 98-117.

Sheets, R. C. (1969): Computations of the seedability of clouds in a hurricane environment. *Project STORMFURY Annual Report 1968,* U.S. Department of Navy and U.S. Department of Commerce, Appendix E.

Sheets, R. C. (1969): Preliminary analysis of cloud physics data collected in hurricane Gladys, 1968. *Project STORMFURY Annual Report 1968*, U.S. Department of Navy and U.S. Department of Commerce, Appendix D.

Simpson, J., and V. Wiggert (1969): Models of precipitation cumulus towers. *Monthly Weather Review, 97*, (7), July, pp. 471-489.

Simpson, J., and W. L. Woodley (1971): Seeding cumulus in Florida--New 1970 results. *Science, 172*, (3979), April 9, pp. 117-126.

Simpson, R. H., M. R. Ahrens, and R. D. Decker (1963): A cloud seeding experiment in Hurricane Esther, 1961. *National Hurricane Research Project Report No. 60*, Weather Bureau, U.S. Department of Commerce, Washington, D.C., 30 pp.

Simpson, R. H., and J. S. Malkus (1964a): A cloud seeding experiment in Hurricane Beulah, 1963. *Project STORMFURY Annual Report 1963*, U.S. Department of Navy and U.S. Department of Commerce, Appendix E.

Simpson, R. H., and J. S. Malkus (1964b): Experiments in hurricane modification. *Scientific American, 211*, pp. 27-37.

Simpson, R. H., and J. S. Malkus (1965): Hurricane modification: Progress and prospects, 1964. *Project STORMFURY Annual Report 1964*. U.S. Department of Navy and U.S. Department of Commerce, Appendix A.

St. Amand, P. (1970): Techniques for seeding tropical cumulus clouds. AMS Second National Conference on Weather Modification, April, Santa Barbara, Cal.

Sundqvist, H. (1970): Numerical simulation of the development of tropical cyclones with a ten-level model. Part I. *Tellus, XXII*, Nov. 4, pp. 359-390.

APPENDIX C

HURRICANE MODELING AT THE NATIONAL HURRICANE RESEARCH LABORATORY (1970)

Stanley L. Rosenthal
National Hurricane Research Laboratory

INTRODUCTION

The major achievement of this period has been the development of a working, asymmetric model of the hurricane (app. D). Substantial progress has, however, also been made in other areas. Brief summaries of these efforts will be given in later sections of this appendix.

Section 2 reviews our more significant achievements in the general area of time-dependent hurricane modeling. Section 3 reviews the specific problem of modeling a Debbie-like field experiment. Section 4 summarizes efforts less directly related to the development of time-dependent models. Section 5 outlines investigations planned by the group for the next few years.

TIME-DEPENDENT MODELS

(a) The Asymmetric Model: As already noted, progress with this model has been sufficient to warrant a separate discussion (app. D) in this year's annual report. An expanded version of appendix D (Anthes, Rosenthal, Trout, 1970) will appear in the *Monthly Weather Review*. A second paper which compares results of the asymmetric model with a symmetric analog of equivalent vertical resolution has also been accepted for publication (Anthes, Trout, and Rosenthal, 1970).

Computing economics dictate rather coarse vertical and horizontal resolution for the asymmetric model. The atmosphere's vertical structure is represented by only three layers and horizontal spacing of grid points is 30 km. The radial extent of the computational domain is approximately 435 km. The version used to obtain the results shown in appendix D did not contain an explicit water vapor cycle. Although the model allows azimuthal variations, the hurricane

retains an isolated, stationary vortex on an f-plane similar in fashion to the circularly symmetric models. Like the circularly symmetric models, this model is a theoretical tool with no potential for dealing skillfully with real data.

Despite obvious deficiencies due to the lack of adequate resolution, the model reproduces many of the observed asymmetrical features of the hurricane. Realistic portrayals of spiral rainbands are obtained. The anticyclonic eddies of the upper troposphere are reproduced as are the observed areas of negative absolute vorticity and anomalous winds.

Since the preparation of appendix D, the asymmetric model has been generalized to include an explicit water vapor cycle and has been recoded for a staggered horizontal grid. The latter reduces local truncation error without either increasing the number of grid points or reducing the spacing between them. A number of experiments have been conducted with the revised model and results even more promising than those described in appendix D have been obtained. These data are now undergoing careful study.

Despite the realism of the results and despite the increased accuracy obtained through horizontal staggering of variables, the model continues to suffer from a lack of adequate resolution. Improvement of the vertical resolution appears to be economically beyond our reach. There is a possibility, on the other hand, that horizontal resolution, at least in the inner core of the hurricane, may be improved through the use of horizontally variable grids.

Two such grid systems have been designed and tested at NHRL. One of these (Anthes, 1970a) is an analytical transformation from a non-orthogonal, variable mesh in physical space to an orthogonal constant mesh in a computational space. This system possesses the following characteristics: (a) The size of a grid element varies smoothly from a minimum value at the center of the array to a maximum along the boundary. (b) Since the variable grid is derived from an analytical transformation, the degree of variability is easily changed. (c) In the limiting case, the variable grid collapses to the familiar two-dimensional, square grid. (d) The distortion associated with the non-orthogonality of the variable grid is minimum at the center and maximum along the boundaries. (e) The machine programming is relatively simple. On the other hand, the transformed equations do contain more nonlinear terms than the original equations which may be a source of difficulty in very long integrations.

The second type of variable grid (Koss, 1970) is composed of a central core of equal area square grid elements surrounded by 'square annuli' of square grid elements of even larger size. The construction defines a family of variable grids. A degenerate member of the family is the familiar "telescope" grid which has been discussed in the literature with reference to local forecasting by numerical methods. However, other members of the family, in which the sizes of grid squares increase rather gradually outward from the central core, seem to be more suitable for the hurricane problem. The advantages of Koss's approach are that Cartesian coordinates are used and, hence, neither transformation terms nor additional nonlinear terms appear in the hydrodynamic equations. A further advantage is that mass and momentum integrals are preserved to within time differencing errors since the equations are expressed in flux form and variable transformation coefficients (similar to map-scale factors) do not appear. The major disadvantage is that machine coding is extremely laborious.

Numerical tests (Anthes, 1970a; Koss, 1970) indicate that both types of variable grids show promise for the hurricane problem. Further tests are planned for both systems.

Two other studies related to the asymmetric model are in progress. It has been suggested that the vertical staggering of variables (see app. D) may severely distort the basic CISK mechanism which drives the model hurricane. While the realism of the results counteracts this suggestion, we are investigating the matter through a linear analysis. The analysis requires solution of a ninth order characteristic equation with complex coefficients. Results are not yet available.

Output data from the asymmetric model are being examined in detail in an attempt to gain greater physical insight into the asymmetric structure of the model storm. With circularly symmetric initial and boundary conditions, the calculation should remain circularly symmetric for all time. Asymmetries are introduced through the initialization procedure and by the fact that the boundaries are not quite circular. Both of these effects tend to excite wave number 4 and, to a lesser extent, wave number 8. However, during the asymmetric stage of the numerical integration, virtually all of the circular variance is contained in wave numbers 1 and 2. An exception to this occurs quite close to the outer boundary where wave number 4 is most significant. The circular variance near the boundary is quite small and, hence, wave number 4, over-all, is rather insignificant.

While the growth of the symmetric part of the systems is understandable from earlier work with symmetric models, and while the dominance of wave numbers 1 and 2 over higher wave numbers is empirically reasonable, we would like to know more about the physical mechanisms involved. The investigation involves a program of harmonic analysis in an attempt to understand the behavior of the governing equations in the spectral domain.

(b) The Seven-Level Symmetric Model: The basic design of this model, as well as typical results to be expected, were documented in three reports which appeared during the year (Rosenthal, 1970a, 1970b, 1970c).

The only significant revisions during the past year (and since the experiments discussed in the papers cited above) are concerned with the boundary layer formulation. Whereas air-sea exchanges of sensible and latent heat had been simulated by some rather pragmatic constraints on the Ekman layer temperatures and humidities, these energy exchanges are now computed explicitly through the bulk aerodynamic method. The constant drag coefficient used in previous experiments has been replaced with Deacon's empirical relationship.

The revised model was used for a number of experiments (Rosenthal, 1970d) in which boundary layer parameters, initial conditions, lateral boundary conditions, and computational domain size were varied.

When the drag coefficient is varied during the immature stage, the response of the model follows linear theory, and growth is more rapid with larger drag coefficients. However, the ultimate intensity reached by model storms varies inversely with drag coefficient. In the mature stage, small decreases of drag coefficient lead to stronger peak winds; but when the drag coefficient is reduced by large amounts, peak winds diminish. In the latter situation, there is insufficient low-level convergence to sustain convection in the storm core.

Oceanic evaporation was found to be an essential ingredient without which immature storms would not develop and mature storms could not sustain themselves. The air-sea exchange of sensible heat was of lesser importance and only small changes occurred when this energy source was completely suppressed. The relative importance of the air-sea exchanges of sensible and latent heat can be explained rather easily (Rosenthal, 1970d).

Comparisons between experiments with open and mechanically closed lateral boundaries show these boundary conditions to be extremely important. For computational domains of 2000 km or less, model storms with closed lateral boundaries are less intense than their counterparts with open lateral boundaries. The intensity of closed systems increases markedly with domain size, while that of open systems varies only slowly with domain size. The experiments indicate that differences due to lateral boundary conditions might be minimized if the computational domain exceeded 2000 km.

Experiments conducted with open lateral boundaries revealed that the structure and intensity of the mature stage of the model cyclone is relatively insensitive to variations in the scale and intensity of the initial perturbation. The time required to reach the mature stage is, however, quite sensitive to these factors.

MODELING AND GUIDANCE FOR PROJECT STORMFURY (1970)

Appendix C of the 1969 Project STORMFURY Annual Report summarized a number of calculations performed with the seven-level symmetric model in which extremely crude attempts were made to simulate a Debbie-like field experiment. (A revised version of that summary appears in the *Monthly Weather Review* (Rosenthal, 1970e).) Additional calculations of this type have been carried out during the last few months and provide results which differ in varying degrees from those reported on last year.

Before proceeding with a discussion of these differences, some words of caution are in order. These comments arise from having an additional year of thought and discussion devoted to the simulation problem. Rosenthal (1970e) pointed out that the assumption of circular symmetry precluded direct comparisons between model calculations and specific real tropical cyclones. It was our feeling at that time, and it continues to be our feeling, that the model should only be considered representative of some sort of "average" hurricane. We pointed out that real hurricanes are strongly influenced by interactions with neighboring synoptic systems and that these interactions may vary markedly in character from storm to storm and cannot realistically be modeled with a symmetric, isolated vortex.

The calculations discussed in Rosenthal (1970d), raise additional questions concerning certain aspects of the model. In previous reports (Rosenthal, 1970e, for example) we have shown the model to yield a highly realistic storm structure during the mature stage. However, since the model has not and cannot be tested using real observations as initial conditions, we cannot examine the model's realism with regard to the time required for it to pass through a series of transients as it proceeds from one slowly varying state to another. Furthermore, Rosenthal (1970d) showed that the time required for a model storm to reach its mature stage varied by several days according to the values of several rather arbitrary parameters (see discussion in Time Dependent Models p. C-1).

Both the field experiments and the model simulations involve adding a small perturbation to a mature hurricane with the hope that it will be unstable. Since no clear-cut theoretical path for establishing the model's credibility with regard to small perturbations is at hand, and since we cannot be entirely certain that Debbie's changes were produced by the seeding, the realism of the model's response to artificial enhancement of the heating functions must also remain an open question. This will be discussed later in this section.

A major difficulty with regard to interpretation of model simulations is related to the so-called "new hypothesis" (discussed elsewhere in this report, see app. B). The artificial enhancement of the model heating functions, which was designed on the basis of the old hypothesis, appears, from a conceptual point of view, to be inconsistent with the new hypothesis.

Under the old hypothesis, the source of this additional heat was attributed to the freezing of supercooled water in the upper tropospheric portions of tall Cb. In the model calculations, this was represented by adding a fixed amount of heat to the upper troposphere over periods of several hours. While valid arguments could be raised concerning the reality of the magnitude of this heat source and the length of time over which it was added, we could at least visualize a clear relationship between the model procedure and the postulated real atmospheric process.

The hurricane could be pictured as a system which continually generates new Cb whose upper tropospheric positions consist of supercooled water. The seeding operation could then be visualized as a process in which this newly generated supercooled water is continually frozen through artificial nucleation. With this view of the field experiment, it is

not unreasonable to attempt a simulation by adding fixed amounts of heat (intended to be the released heat of fusion) to the upper troposphere at each time step for some period of time.

Under the new hypothesis, however, heat of fusion released through silver iodide nucleation is considered only as a stimulus for increasing the buoyancy of Cb (outward from the main eyewall) which by natural processes would reach only to middle tropospheric levels. Under this hypothesis, the major source of energy for modification purposes is sought in the additional condensation and/or sublimation heating released as the seeded clouds grow to upper tropospheric levels.

The difficulty with a simulation relevant to the new hypothesis is that all model Cb which originate in the boundary layer reach upper tropospheric levels by natural processes. This stems from the fact that the model Cb are comprised of undilute ascent. Entrainment is not taken into account. With the current version of the model, therefore, the eyewall region differs from other regions of the storm in *cloud concentration but not in cloud depth.*

Simulation of the new hypothesis is then not easily visualized unless one adopts a highly philosophical attitude. One can, however, argue as follows. The basic feature of the new hypothesis is the stimulation of tall convection at radii larger than that of the eyewall in the hope of diverting some of the boundary layer inflow thus reducing the supply of moisture and angular momentum to the eyewall region. In the field experiment, this is to be accomplished by causing relatively short clouds to become tall as described in a previous paragraph. In the model, where all clouds are tall, a conceivable analogue to the field experiment is to increase the *concentration* of tall clouds at the corresponding radii. Once this point of view has been accepted, the means by which model convection is stimulated becomes rather arbitrary.

The addition of a fixed amount of heat as in Rosenthal (1970e) is only one of many possibilities. Others include arbitrary changes of boundary layer convergence, changes of the humidity patterns, and changes in static stability. Of course, these alterations can also be made in various combinations.

While calculations of the Rosenthal (1970e) type can still provide helpful information for Project STORMFURY if properly interpreted, clearly literal comparisons between the calculations and the Debbie experiment are unwarranted. Aside from the arbitrary procedures used to simulate seeding,

the questions concerning the response time of the model raised earlier in this section must be considered as must the lack of interaction with other synoptic features.

It is abundantly clear that we must strive to provide more direct numerical tests of the new hypothesis. To achieve this end, it will be essential to include entrainment and some simple representation of the more significant microphysical processes. It may also be necessary to make improvements in the modeling of the interactions between the Cb and hurricane scales. This will be a high priority item for the next year.

In the meantime, calculations of the old type will continue. These have and will continue to provide useful information when compared against each other. As noted earlier, differences of varying degree have arisen between the calculations reported on last year and those performed in recent months. Some of these differences are probably attributable to a revision of the model during the intervening period. This revision consisted of replacement of the constant drag coefficient (3×10^{-3}) by Deacon's empirical relationship (see discussion in Section 2). The latter gives a linear dependence on wind speed, and values of 3×10^{-3} are not reached until winds approach 50 m sec^{-1}.[1] A second source of the differences may well be that model response to the heating enhancement is dependent on the initial conditions. A series of controlled experiments is planned to study this aspect of the problem.

To make meaningful comparisons between the results presented in the 1969 report and those obtained more recently, the former are briefly summarized below. Heating rates were increased at 500 and 300 mb by 1 kj-ton^{-1} sec^{-1} (*normal heating*), 3 kj-ton^{-1} sec^{-1} (*large heating*), and 9 kj-ton^{-1} sec^{-1} (*extreme heating*) for 10-hour intervals at various radii. The radial intervals selected were 25, 35, and 45 km (*small radii* experiments) and 35, 45, and 55 km (*large radii* experiments). The sea-level wind maximum for the control experiment was at 20 km. Hence, in both the *small* and *large radii* experiments, the heat was applied at radii beyond the sea-level wind maximum. The center of the eyewall for the control experiment was at 25 km radius. The *small radii* calculations, therefore, add heat from the eyewall center outward whereas the *large radii* experiments do not add heat at the eyewall center. Experiments were also conducted in which heat was added from the eyewall center inward.

---

[1] For a discussion of the effect of this change on the typical results to be expected from the model, the reader is referred to Rosenthal (1970d).

Small and *large radii* experiments were consistent in showing the development of a new eyewall at 35 km and destruction of the original eyewall. A new surface-wind maximum was consistently formed at a radius of 40 km, and the original maximum (at 20 km) was eventually destroyed. In general, the newly formed maximum was about 5 m sec^{-1} less intense than the original.

With *normal heating at small radii*, the time required for the new wind maximum to become established was about 8 hours. Differences between *small and large radii* experiments with *normal heating* were minor. In both of these experiments, however, prior to the development of the new wind maximum, winds stronger than the control were found at all radii. *Extreme heating* experiments differed from *normal heating* calculations only in response time. *Extreme heating* at *large radii* gave results which differed from *extreme heating* at *small radii* also only in response time. With *extreme heating* at *large radii*, the new surface-wind maximum was established within 2 hours. *Extreme heating* at *small radii* required 4 hours to establish the new velocity maximum. Prior to this time, surface winds in the modified calculation were as large as 5 m sec^{-1} greater than in the control. Application of the extreme heating rate inside the radius of maximum wind resulted in surface wind increases of 3 m sec^{-1}. However, when the artificial heating was terminated, the system recovered to a state close to that of the control within 4 hours. In contrast, the *large* and *small radii* experiments reached rather stable configurations which were maintained even after the artificial heating was terminated.

While the general evolution of the sea-level winds in the experiments described above was in the sense predicted by either the "old" or the "new" hypothesis, the model's behavior at 700 mb raised some questions. The sense of the 700 mb changes was more or less similar to those changes at sea level. However, the 700 mb responses were more rapid and extreme. The early intensification found at the surface was even more pronounced at 700 mb. The new wind maximum, when formed at 700 mb, was generally more intense than the original maximum until after termination of the enhanced heating.

The major difference between the experimental results just summarized and those obtained more recently is that for a given rate and location of heating, the response times are greater and the magnitudes of the responses are less in the new calculations. In the new experiments, normal heating at *small radii* requires 14 hours to develop the new wind maximum at sea level. Furthermore, in all of the new experiments, the new wind maximum is generated only 10 km outward from the

original maximum. In the old calculations the displacement was 20 km. In the old calculations, with the *normal heating* rate, the magnitude and timing of the response were similar for both *large* and *small* radii experiments. In the new calculations, *normal heating* at *large radii* generates the new sea-level wind maximum about 6 hours earlier than does *normal heating* at *small radii*. Calculations with the ½ the *normal heating* rate at *small radii* shows an ultimate effect similar to that obtained for the experiments with *normal heating*. However, approximately 3½ days of enhanced heating are required to obtain the effect.

Despite the differences which have been emphasized in the last few paragraphs, the experiments do show a consistent pattern which is useful for the design of field experiments. Enhancement of the upper tropospheric heating functions for a sufficiently long period at *radii greater* than the eyewall center and surface wind maximum will ultimately produce a new eyewall and a new, less intense, sea-level wind maximum at radii greater than those of the "naturally" occurring features. The time required to produce these changes is reduced as the rate of heating enhancement is increased. Application of enhanced heating from the eyewall center inward or only at the eyewall center will result in stronger winds at sea level. In this case, the eyewall and the wind maximum will remain at the natural locations.

OTHER INVESTIGATIONS

Anthes (1970b) examined the role of azimuthal asymmetries in satisfying the mean angular momentum budget for the steady-state hurricane.

Anthes (1970c) developed a circularly symmetric model in isentropic coordinates to study the effects of differential heating on the dynamics and energetics of the steady-state tropical cyclone. From specified heating functions, he obtained nearly steady-state solutions for the mass and momentum fields. These solutions were then used to evaluate the available potential energy cycle for the theoretical hurricane. The major results of this investigation will appear in the *Monthly Weather Review* (Anthes, 1970d, 1970e).

Anthes (1970f) examined the problem of truncation error in the calculation of vertical motions at the top of the Ekman layer under an imposed hurricane-like, circularly symmetric pressure field.

Black and Anthes (1971) constructed detailed wind analyses of the outflow layer for four hurricanes and one tropical storm. Harmonic analysis of these data, together with that of the composite storms of Miller and Izawa, shows wave numbers 1 and 2 to account for most of the circular variance in the momentum and kinetic energy fields.

FUTURE PLANS

High priority will be given the development of a more sophisticated cloud representation to be used with the seven-level, circularly symmetric hurricane model so that closer simulations of the "new" STORMFURY hypothesis may be performed.

Simulations of hurricane seeding will be carried out with the asymmetric hurricane model during the next year.

Horizontal resolution in the central portions of the asymmetric hurricane model may be improved through recoding for one of the variable mesh systems discussed in Section 2. Beyond this, the next logical step would seem to be removal of the stationary, isolated vortex assumptions. This will be a major step and will increase our computing requirements by an order of magnitude.

We envision a model in which a fine mesh moves with the hurricane center through a coarse mesh on which the large-scale synoptic patterns are forecast. This type of model will not only serve as a theoretical tool but also will have the potential for real hurricane forecasting. Whether or not this potential will ever be realized will, to a major extent, be dependent upon the development of real time observational techniques for providing adequate high resolution initial data (~10 km horizontal resolution) in the hurricane vortex.

To develop such a model, important background investigations will be required. The mathematical and physical considerations for linking a moving fine mesh with a stationary coarse mesh in the framework of a primitive equation model will require extensive research. The problem of hurricane displacement forecasting by dynamic methods must be reexamined. It is not clear whether the characteristic errors of the existing filtered (primarily barotropic) models are primarily a result of erroneous initial data or physical simplifications.

While these problems must ultimately be faced in the real data context, it is our feeling that the most promising start lies with the use of hypothetical initial data and a philosophical attitude similar to that adopted for our earlier work.

REFERENCES

Anthes, R. A. (1970a): Numerical experiments with a two-dimensional horizontal variable grid. *Monthly Weather Review, 98,* (11), November, pp. 810-822.

Anthes, R. A. (1970b): The role of large-scale asymmetries and internal mixing in computing meridional circulations associated with steady-state hurricanes. *Monthly Weather Review, 98,* (7), July, pp. 521-529.

Anthes, R. Z. (1970c): A diagnostic model of the tropical cyclone in isentropic coordinates. ERLTM-NHRL Technical Memorandum No. 89, ESSA, U.S. Dept. of Commerce, NHRL, Miami, Fla., 147 pp.

Anthes, R. A. (1970d): A numerical model of the steady-state tropical cyclone in isentropic coordinates. Paper accepted for publication in the *Monthly Weather Review.*

Anthes, R. A. (1970e): Numerical experiments with a steady-state model of the tropical cyclone. Paper accepted for publication in the *Monthly Weather Review.*

Anthes, R. A. (1970f): Iterative solutions to the steady-state axisymmetric boundary layer equations under an intense pressure gradient. Paper accepted for publication in the *Monthly Weather Review.*

Anthes, R. A., S. L. Rosenthal, and J. W. Trout (1970): Preliminary results from an asymmetric model of the tropical cyclone. Accepted for publication in the *Monthly Weather Review.*

Anthes, R. A., J. W. Trout, and S. L. Rosenthal (1970): Comparisons of tropical cyclone simulations with and without the assumption of circular symmetry. Accepted for publication in the *Monthly Weather Review.*

While these problems must ultimately be faced in the real data context, it is our feeling that the most promising start lies with the use of hypothetical initial data and a philosophical attitude similar to that adopted for our earlier work.

REFERENCES

Anthes, R. A. (1970a): Numerical experiments with a two-dimensional horizontal variable grid. *Monthly Weather Review, 98,* (11), November, pp. 810-822.

Anthes, R. A. (1970b): The role of large-scale asymmetries and internal mixing in computing meridional circulations associated with steady-state hurricanes. *Monthly Weather Review, 98,* (7), July, pp. 521-529.

Anthes, R. Z. (1970c): A diagnostic model of the tropical cyclone in isentropic coordinates. ERLTM-NHRL Technical Memorandum No. 89, ESSA, U.S. Dept. of Commerce, NHRL, Miami, Fla., 147 pp.

Anthes, R. A. (1970d): A numerical model of the steady-state tropical cyclone in isentropic coordinates. Paper accepted for publication in the *Monthly Weather Review.*

Anthes, R. A. (1970e): Numerical experiments with a steady-state model of the tropical cyclone. Paper accepted for publication in the *Monthly Weather Review.*

Anthes, R. A. (1970f): Iterative solutions to the steady-state axisymmetric boundary layer equations under an intense pressure gradient. Paper accepted for publication in the *Monthly Weather Review.*

Anthes, R. A., S. L. Rosenthal, and J. W. Trout (1970): Preliminary results from an asymmetric model of the tropical cyclone. Accepted for publication in the *Monthly Weather Review.*

Anthes, R. A., J. W. Trout, and S. L. Rosenthal (1970): Comparisons of tropical cyclone simulations with and without the assumption of circular symmetry. Accepted for publication in the *Monthly Weather Review.*

APPENDIX D

SUMMARY OF PRELIMINARY RESULTS FROM AN ASYMMETRIC MODEL OF THE TROPICAL CYCLONE[1]

Richard A. Anthes, Stanley L. Rosenthal, and James W. Trout
National Hurricane Research Laboratory

ABSTRACT

A three layer, primitive equation model of an isolated stationary tropical cyclone is constructed. The major difference between this and previously published models is the elimination of the assumption of circular symmetry. The release of latent heat by the organized cumulus convection is parameterized by use of techniques previously shown to give realistic results in symmetrical models. In particular, the total release of heat in a vertical column is given by the horizontal convergence of water vapor in the Ekman layer, and the vertical distribution of the heating follows the proposals made by Kuo (1965). In this preliminary calculation, water vapor content is not forecast but, rather, is treated implicitly as was the case for the earlier circularly symmetric models.

The results show that the model reproduces many observed features of the three-dimensional tropical cyclone. Realistic portrayals of spiral rainbands and the strongly asymmetric structure of the outflow layer are obtained. The kinetic energy budget of the model compares favorably with empirical estimates and also shows the loss of kinetic energy to truncation errors to be very small.

Large scale horizontal asymmetries in the outflow are found to play a significant role in the radial transport of vorticity during the mature stage and are of the same magnitude as the transport by the circulation.

In agreement with empirical studies, the outflow layer of the model storm shows substantial areas of negative absolute vorticity and anomalous winds.

---

[1] This report summarizes a more complete version to be published in the *Monthly Weather Review* in 1971.

INTRODUCTION

Axisymmetric numerical models have simulated the life cycle of tropical cyclones with a large degree of realism (Goyama, 1969; Yamasaki, 1968a, 1968b; Rosenthal, 1970b). They have also yielded valuable insight into hurricane dynamics, energetics, and the important problem of parameterizing the latent heat released in organized cumulus convection. With this background, and with ever increasing computer capability, it is not premature to begin the study of the asymmetric features of the hurricane. Among the more notable of these are the upper tropospheric outflow layer, the rainbands, hurricane motion, and the interactions between the hurricane and nearby synoptic systems.

To incorporate all of these features in a single numerical model is an extremely ambitious goal that will require further investigation. The model developed here represents an isolated stationary vortex and appears to be the logical first step beyond the axisymmetric models. For computational economy, we have limited the model to three vertical levels, a coarse horizontal resolution of 30 km, and a relatively small domain of radius 435 km.

DESIGN OF MODEL

The equations of motion are written in σ coordinates (Phillips, 1957) on an f-plane, where f, the Coriolis parameter, is appropriate to approximately 20°N (5×10^{-5} sec^{-1}). The equations of motion, continuity equation, thermodynamic equation, and hydrostatic equation are identical to those employed by Smagorinsky et al. (1965) for general circulation studies. The basic equations are given in Anthes et al. (1971a), hereafter referred to as I, and are not repeated here.

STRUCTURE OF THE MODEL

The vertical structure of the model is shown by figure D-1a. The atmosphere is divided into upper and lower layers of equal pressure depth and a thinner Ekman boundary layer. The information levels for the dynamic and thermodynamic variables (fig. D-1a) are staggered according to the scheme used by Kurihara and Holloway (1967).

The horizontal mesh (fig. D-1b) is rectangular with a uniform spacing of 30 km. The lateral boundary points approximate a circle, and all boundary points are contained between radii of 450 and 435 km. All variables are defined at all grid points on the σ-surfaces.

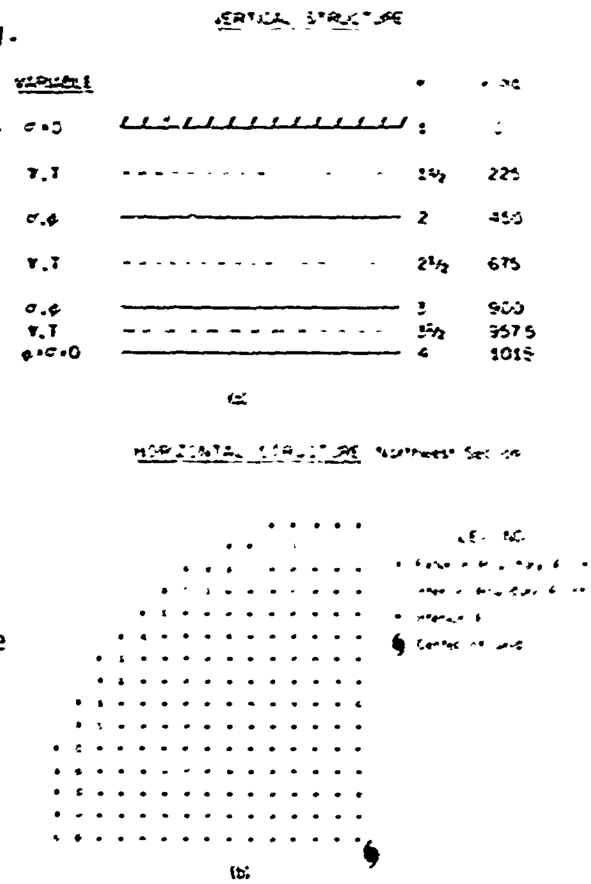


Figure D-1. (a) Vertical information levels; (b) Northwest quadrant of the horizontal grid.

THE FINITE DIFFERENCE EQUATIONS

The finite difference analogs to the horizontal derivatives are similar to those in Grammeltvedt's (1969) scheme "B". The vertical portion of the differencing scheme is identical to that of Kurihara and Holloway (1967) with the exception that potential temperature rather than temperature is interpolated where needed. The details are given in I.

For adiabatic, inviscid flow in a laterally closed domain with $\dot{\sigma} = 0$ at $\sigma = 0$ and 1, Kurihara and Holloway showed this system to conserve the finite difference analog to

$$\int_x \int_y \int_0^1 p^* \left[C_p T + \frac{u^2 + v^2}{2} \right] d\sigma dy dx. \qquad (D.1)$$

VERTICAL DIFFUSION OF MOMENTUM

Although vertical transport of horizontal momentum by the cumulus-scale motions has been shown to be an important element in maintaining the observed structure of hurricanes (Gray, 1967; Rosenthal, 1970b), this effect is not included in the preliminary calculations reported on here. Therefore,

vertical diffusive and "frictional" effects in this experiment are due to the vertical transports of horizontal momentum by subgrid scale eddies smaller than the cumulus scale. The most important aspect of these terms is the surface drag which produces frictional convergence in the cyclone boundary layer and, therefore, a water vapor supply which controls the parameterized cumulus convection (Charney and Eliassen, 1964; Ooyama, 1969; Rosenthal, 1970b).

The surface drag is modeled using the well-known quadratic stress law, and a constant value of 3×10^{-3} was adopted for C_D. For the remaining σ-levels we use the Austausch formulation with the Rossby-Montgomery formulation adopted for the vertical kinematic coefficient of eddy viscosity, K_z (Smogorinsky et al., 1965). The details are given in I.

LATERAL MIXING TERMS

After Smagorinsky et al. (1965), the lateral exchange of horizontal momentum by subgrid scale eddies is written

$$F_H(\vec{V}) = \frac{\partial}{\partial x}\left(K_H \frac{\partial p^*\vec{V}}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H \frac{\partial p^*\vec{V}}{\partial y}\right) \qquad (D.2)$$

where $\vec{V}$ is the horizontal vector velocity, p^* is surface pressure, and K_H is the horizontal coefficient of eddy viscosity.

Preliminary tests, as well as calculations with a symmetrical analog to this model (Anthes et al., 1971b) revealed that neither a constant value of K_H nor Smagorinsky's (1965) variable K_H (proportional to the magnitude of the total deformation of the horizontal motion) provided acceptable results.

The formulation ultimately adopted was

$$K_H = C_1|V| + C_2 \qquad (D.3)$$

where $C_1 = 10^3$ and $C_2 = 5 \times 10^3 m^2 \sec^{-1}$.

While this selection was based primarily on the results of numerical tests, the form was suggested by the encouraging results obtained from symmetrical models (Rosenthal, 1970b; Yamasaki, 1968b) which employed upstream differencing of advection terms with forward time steps. This scheme introduces a computational viscosity (Molenkamp, 1968) which is similar to the variable portion of (D.3).

Although (D.3) is not terribly satisfying from a physical point of view, it does afford a useful interim representation of the statistical effect of horizontal interactions between the momentum fields of the cumuli and macroscale. More satisfying formulations are dependent on the success of future theoretical and observational studies of these interactions.

The preliminary tests also indicated that adequate results can be obtained if the lateral diffusion of heat is computed with a constant thermal diffusivity (K_T) of 5 x 10^4 m^2 sec^{-1}. The lateral mixing term in the thermodynamic equation was, therefore, expressed in the form

$$F_H(T) = p^* K_T \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right), \qquad (D.4)$$

where T is temperature.

TIME INTEGRATION

A number of experiments were conducted for the purpose of selecting a method of time integration. Comparisons were made between the usual leap-frog method, the two-step Lax-Wendroff scheme (Richtmyer and Morton, 1967), and the Matsuno (1966) simulated forward-backward scheme. With viscous and diabatic effects included, the Matsuno technique was clearly superior to the other schemes tested. This conclusion was based on intuitive meteorological inspection of the test results. Presumably, the superiority of the Matsuno scheme is due to its severe damping of high temporal frequencies. Since this model has very limited vertical resolution, the high-frequency inertia-gravity waves (particularly, the external gravity wave) are probably overly excited by the diabatic heating. The Matsuno damping may, then, compensate for this effect.

LATERAL BOUNDARY CONDITIONS

The small domain size and the irregular boundary make the choice of lateral boundary conditions extremely important. Preliminary experimentation showed that realistic results could be obtained for steady-state pressure and temperature on the boundary and a variable momentum based on extrapolation outward from the interior of the domain.

LATENT HEAT RELEASED IN ORGANIZED CUMULUS CONVECTION

As already noted, this preliminary experiment does not contain an explicit water cycle. Because of this, the convective adjustments of macroscale temperature are parameterized as they were in the original version of Rosenthal's (1969) symmetric model. The formulation contains ingredients suggested by previous investigators - particularly, Charney and Eliassen (1964); Kuo (1965); Ogura (1964); Ooyama (1969); Syōno and Yamasaki (1966); Yamasaki (1968a, b).

The basic characteristics of this convective adjustment are summarized as follows:

1. Convection occurs only in the presence of low-level convergence and conditional instability for air parcels rising from the surface.
2. All the water vapor that converges in the boundary layer rises in convective clouds, condenses, and falls out as precipitation.
3. All the latent heat thus released is made available to the macroscale flow.
4. The vertical distribution of this heating is such that the macroscale lapse rate is adjusted towards the pseudo-adiabat appropriate to ascent from the surface.

Empirical justfication for these characteristics is presented by Rosenthal (1969).

The convective adjustment, described above, applies only when the atmosphere is conditionally unstable; i.e., the cloud temperature, T_c, exceeds the environmental temperature, T. In mature hurricanes, however, prolonged and intense cumulus convection substantially reduces parcel buoyancy and lapse rates approach the moist adiabatic. Under these circumstances, significant amounts of nonconvective precipitation (and, hence, latent heat release) may occur (Hawkins and Rubsam, 1968). Since, in this experiment, water vapor is not explicitly forecast, it is necessary to parameterize this effect.

The parameterization of nonconvective latent heat release under nearly moist adiabatic conditions proceeds as follows. Whenever $(T_c - T) < 0.5°C$ in the middle or upper tropospheric layers, this quantity is arbitrarily set to 0.5°C. Under a nearly moist adiabatic lapse rate, therefore, $T_c - T = 0.5°C$ at both levels, and the latent heat is partitioned equally between the upper and lower troposphere. Therefore, latent heat is released in the column as long as a water vapor supply from the boundary layer is present.

The value of specific humidity, q, in the boundary layer, needed for the evaluation of the moisture convergence, is assumed to be given by

$$q = \text{minimum} \begin{Bmatrix} 0.90 \quad q_s \\ 0.020 \end{Bmatrix} \qquad (D.5)$$

where q_s is the saturation specific humidity. The upper boundary of 0.020 avoids excessive moisture values at points close to the storm center in the late stages of development when warm temperatures associated with an "eye" appear.

Finally, the surface humidity and temperature are required to establish the pseudoadiabat appropriate to parcel ascent from the surface.

The surface temperature, T*, is computed by a downward extrapolation from the temperature at level k = 7/2 assuming a constant lapse rate between the dry and moist adiabatic rates. The surface specific humidity, q*, is obtained from q through the assumption that the relative humidity is constant in the boundary layer.

AIR-SEA EXCHANGE OF SENSIBLE HEAT

The sensible heat flux at the air-sea interface is assumed to obey the bulk aerodynamic relationship. It is further assumed that the heat flux decreases linearly with σ until it reaches a value of zero at the k = 3 level. This gives

$$p^*\dot{Q}^S_{k=7/2} = \begin{Bmatrix} \dfrac{gC_p C_E |V| \rho^* (T_{sea} - T^*)}{\sigma_4 - \sigma_3}, & T_{sea} > T^* \\ 0, & T_{sea} \leq T^* \end{Bmatrix} \qquad (D.6)$$

where $\dot{Q}^{s}_{k=7/2}$ is the sensible heat added per unit mass and time at k = 7/2. The exchange coefficient C_E is taken equal to C_D (0.003); T_{sea} = 302°K is used for the experiment discussed below.

INITIAL CONDITIONS

The initial conditions consist of an axisymmetric vortex in gradient balance. The minimum pressure is 1011 mb and the environmental pressure on the lateral boundaries is 1015 mb, yielding a maximum gradient wind of 18 m sec^{-1} at a radius of 240 km.

EXPERIMENTAL RESULTS

The history of the cyclone is summarized by figure D-2 which shows the evolution of the minimum surface pressure and the maximum wind speed in the boundary layer (k = 7/2). Due

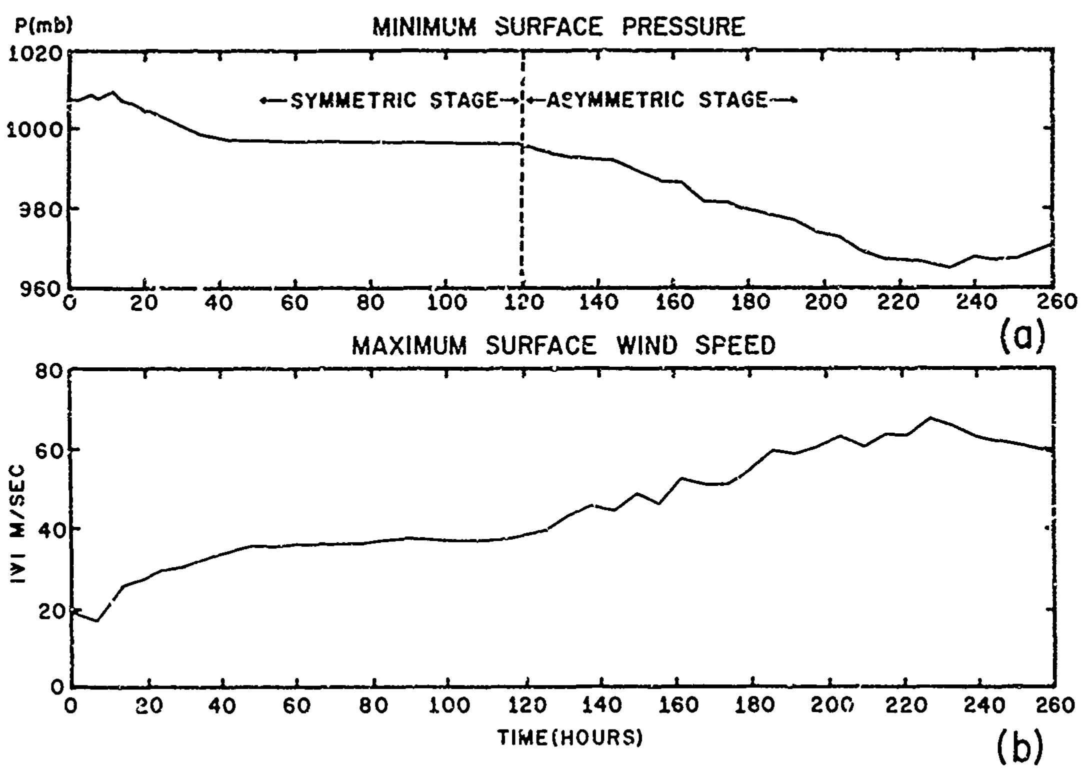


Figure D-2. Time variation of the minimum surface pressure and the maximum surface wind speed.

to the substantial strength of the initial vortex, a short "organizational phase" of only 12 hours is needed before steady intensification begins. Hurricane force winds appear at about 40 hours and, thereafter, the relatively weak storm remains in a quasi-steady state until about 120 hours. At this point, a second period of intensification begins and the maximum wind eventually exceeds 60 m sec^{-1}. The unsteady nature of the storm during this period seems to be related to the development of pronounced asymmetries (especially in the outflow region). These asymmetries are discussed in detail later.

Figure D-3 shows the temporal variations of the components of the kinetic energy budget. The sum of, (1) the conversion of potential to kinetic energy (C(K)), (b) the flux

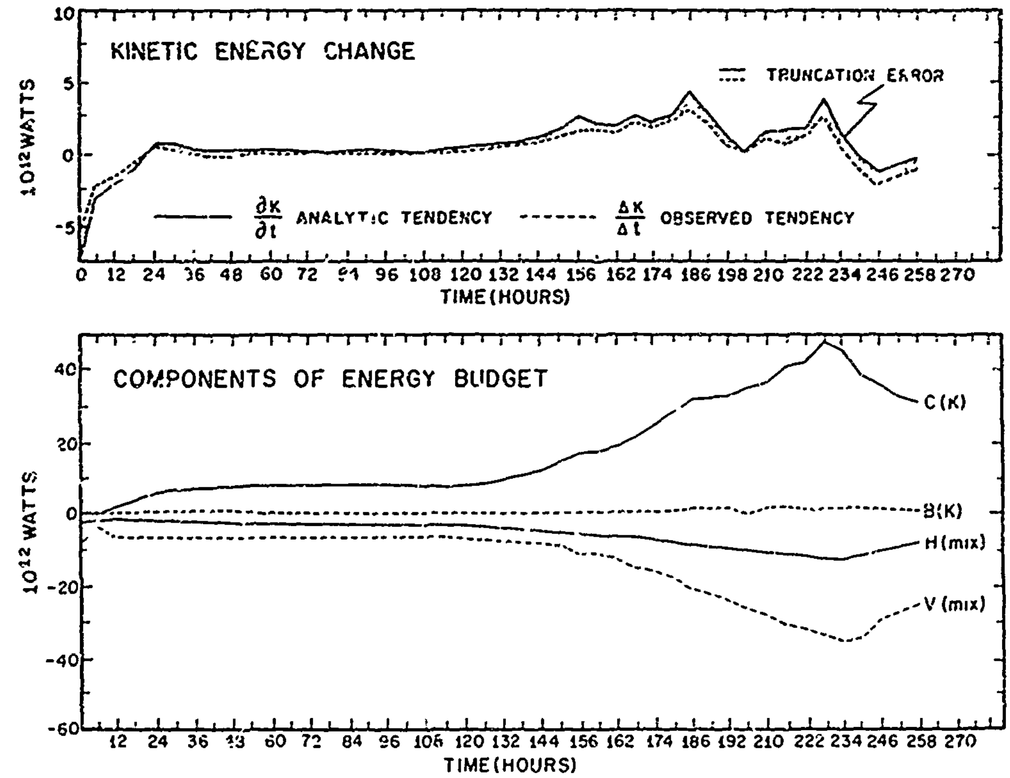


Figure D-3. (a) Time variation of the observed kinetic energy ($\Delta k/\Delta t$) and the change computed from the kinetic energy equation ($\partial k/\partial t$): (b) Time variation of individual components of the kinetic energy tendency: C(k) is the conversion of potential to kinetic energy, B(k) is the flow of kinetic energy through the lateral boundary, H(mix) is the loss of kinetic energy through lateral eddy viscosity, V(mix) is the loss of kinetic energy through vertical eddy viscosity and includes the effect of surface drag friction.

of kinetic energy across the lateral boundary (B(K)), (3) the dissipation due to lateral mixing (H(mix)), and (4) the dissipation due to vertical mixing (V(mix)) equals the "analytic" kinetic energy tendency ($\partial k/\partial t$). Also shown by figure D-3 are the observed rates of change of kinetic energy ($\Delta k/\Delta t$). The difference between $\partial k/\partial t$ and $\Delta k/\Delta t$ is a measure of the truncation error and, as figure D-4 shows, this difference is quite small. Furthermore, the individual components of the budget are reasonable when compared to empirical estimates (Hawkins and Rubsam, 1968; Miller, 1962; Palmén and Riehl, 1957; and Riehl and Malkus, 1961).

For purposes of discussion, it is convenient to divide the history of the storm into two stages. From the initial instant until about 120 hours, all features are quite symmetric with respect to the storm center. During this period, there is neither evidence of a banded structure in the rainfall (analogous to rainbands in real hurricanes) nor does the

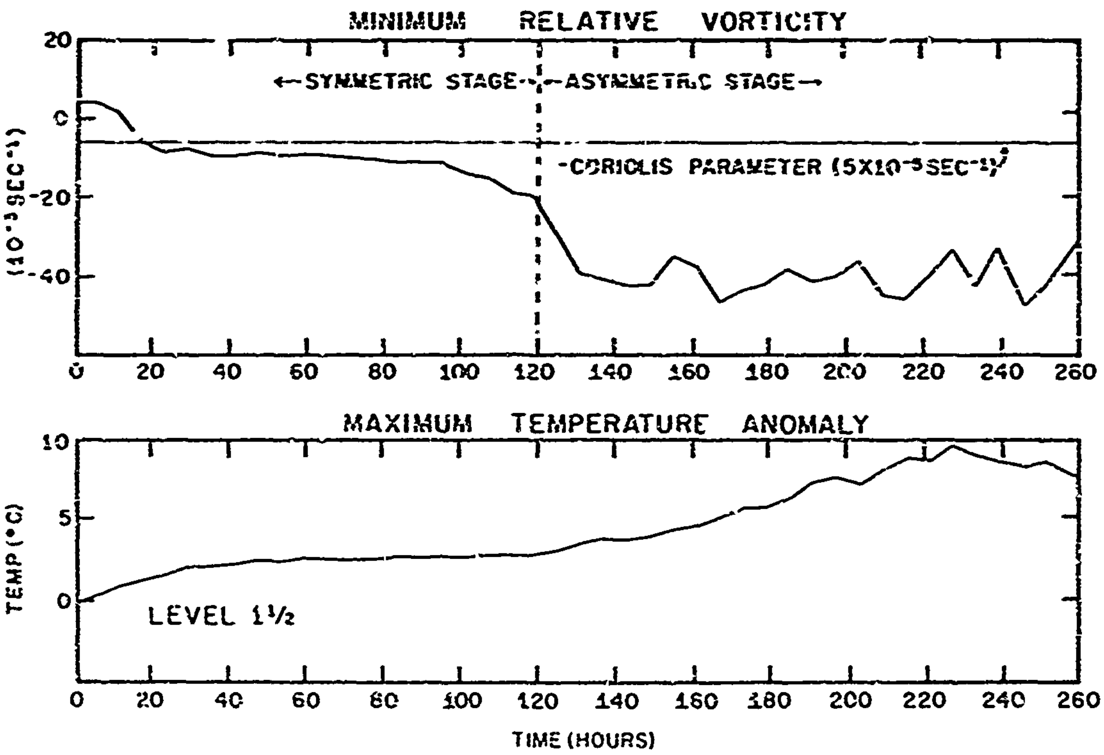


Figure D-4. (a) Time variation of the minimum relative vorticity in upper troposphere (level 1½); (b) Time variation of the maximum temperature anomaly (departure of temperature from the steady-state value at the lateral boundary) in the upper troposphere (level 1½).

upper tropospheric outflow show any preference for particular quadrants. We refer to this interval as the "early symmetric stage." After 120 hours, the upper outflow is quite asymmetric while the rainfall and vertical motions show distinct patterns analogous to the spiral rainbands found in real storms. We refer to this period as the "asymmetric stage." The "symmetric" and "asymmetric" stages refer to the model calculation only, and, because of the arbitrary nature of the initial conditions, are not meant to have direct counterparts in natural storms.

EARLY, SYMMETRIC STAGE OF THE MODEL STORM

A representative view of the structure during this period is provided by the data at 84 hours. The region of hurricane force winds is very small, extending only about 75 km from the center. Gale force winds extend outward to 150 km. The maximum tangential and radial winds are 34.0 m sec^{-1} and -19.4 m sec^{-1}, respectively, yielding an inflow angle of about 29 degrees.

The circulation in the upper troposphere (level $1\frac{1}{2}$) shows a fairly symmetric outflow pattern. Cyclonic outflow occurs inside a radius of about 200 km. Beyond 200 km, the circulation is anticyclonic, reaching a maximum velocity of about 6 m sec^{-1} around the outer boundary. The figures are shown in I.

Dynamic (or inertial) instability of the upper tropospheric outflow has been suggested by Alaka (1961, 1962, 1963) and others as a contributory factor in the intensification of tropical cyclones. An approximate necessary condition for this instability is given by

$$\zeta_a \left(\frac{2|\vec{V}| + f}{R}\right) < 0 \qquad (D.7)$$

where $|\vec{V}|$ is the wind speed, R is the radius of curvature of the streamlines, and ζ_a is the absolute vorticity.

Strictly speaking, this criterion for instability refers to horizontal parcel displacements normal to a streamline and is derived under the assumption that the velocity and pressure fields are invariant along the streamline. A

necessary criterion for a closely related instability is

$$\left(\frac{\partial v_\lambda}{\partial r} + \frac{v_\lambda}{r} + f\right)\left(\frac{2v_\lambda}{r} + f\right) < 0 \;. \qquad \text{(D.8)}$$

The criterion (D.8) relates to the instability of horizontal symmetric fluid ring displacement in a symmetric vortex.

A third type of dynamic instability is governed by the necessary condition that the radial gradient of the absolute vorticity of the tangential flow have at least one zero. That is, the condition

$$\frac{\partial}{\partial r}\left\{\frac{\partial v_\lambda}{\partial r} + \frac{v_\lambda}{r} + f\right\} = 0 \;, \qquad \text{(D.9)}$$

is satisfied somewhere in the fluid system. This is a necessary condition for asymmetric (azimuthally varying) horizontal perturbations to be unstable.

At the initial instant, when the flow is nearly symmetric and tangential, (D.7) and (D.8) become equivalent. Since the initial data satisfy neither condition, these instabilities do not contribute to the very early intensification. On the other hand, (D.9) is satisfied even in the initial data since there is a maximum of cyclonic vorticity close to the center of the storm and a vorticity minimum (maximum of anticyclonic relative vorticity) at a radius of approximately 345 km. This should favor the growth of wave-like perturbations in the azimuthal direction. Since weak waves of this type are present in the initial data due to round-off differences, and since, as already noted, substantial symmetry is retained for the first 120 hours, it is clear that the instability is either quite weak or that it is being counteracted by other effects such as those due to eddy viscosity.

Figure D-4 shows the time evolution of the minimum value of relative vorticity in the upper level within 350 km of the storm center. During the initial deepening stage the minimum value of absolute vorticity becomes slightly negative. However, this occurs after the intensification and only over a small region.

The term $(2|\vec{V}|/R + f)$ was also evaluated for several times during the first 120 hours. These calculations revealed only small patches of anomalous winds. We, therefore, also feel that the instabilities represented by (D.7) and (D.8) played no significant role in the early symmetric stage of the model storm.

Azimuthally averaged vertical cross sections provide an adequate description of the storm structure during the early symmetric stage. Mean cross sections[2] for the tangential wind, radial wind, and the temperature departure at 84 hours are shown by figure D-5. These cross sections reveal a structure very typical of that of a weak hurricane (Hawkins and Rubsam, 1968).

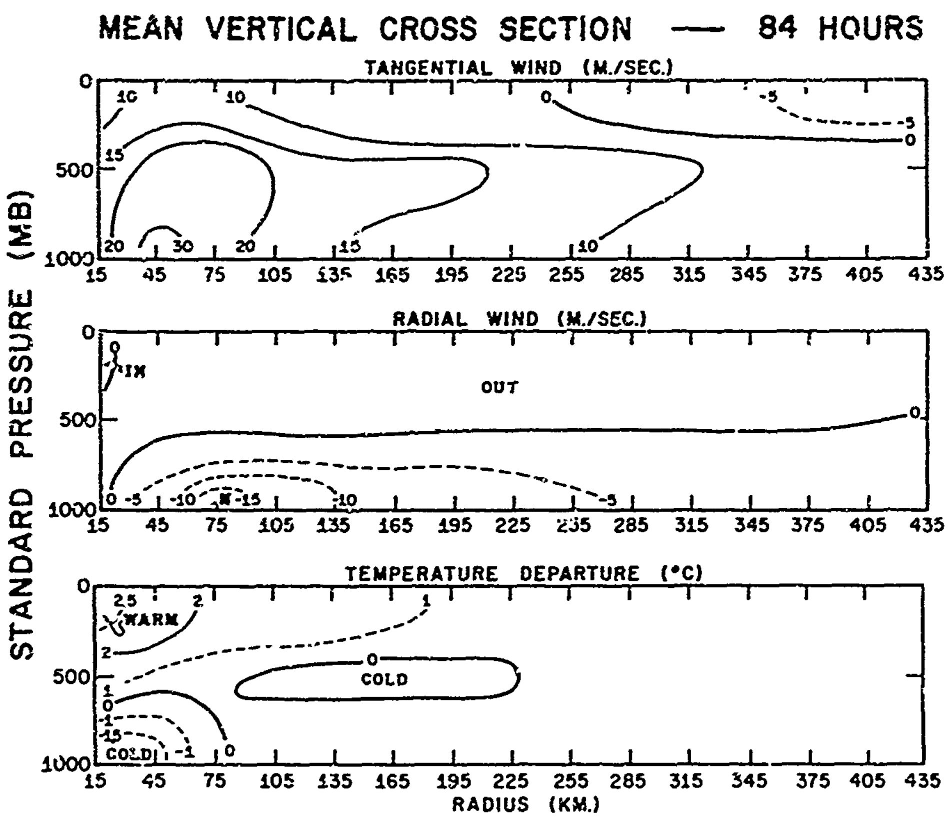


Figure D-5. Azimuthal mean vertical cross sections for the tangential wind, the radial wind, and the temperature anomaly at 84 hours. Isotherms are labeled in °C; isotachs are labeled in m sec^{-1}.

[2] The circular averages were computed through linear interpolation of gridpoint values to a polar grid with a radial increment of 30 km and an angular increment of 22.5 degrees.

The vertical motion at the top of the boundary layer at 84 hours shows a nearly circular region of upward motion that extends from the center to about 180 km. Maximum velocities of about -140 mb hour^{-1} (about 0.4 m sec^{-1}) occur in a ring near the center. Weak subsidence occurs in the environment beyond 180 km. The strongest upward velocities occur in the middle troposphere (level 5/2) and reach -230 mb hour^{-1} (about 0.7 m sec^{-1}). These values appear reasonable for averages over a 30 km interval of a weak hurricane (Carlson and Sheets, 1971).

The average rainfall over the inner 100 km, computed by conversion of the total release of latent heat in a column to the equivalent water depth, is 65 cm day^{-1} which is comparable with the estimates made by Riehl and Malkus (1961) for Hurricane Daisy (1958). The total release of latent heat at this time is 5.0 x 10^{14} W. This also compares favorably with empirical estimates (Anthes and Johnson, 1968). Finally, the rainfall pattern at 84 hours shows no evidence of spiral bands.

Figure D-6 shows surface pressure profiles for various times along one radius from the center of the grid. Since the surface isobars are very nearly circular, these profiles provide an adequate description of the surface pressure field. The minimum value at 84 hours (995 mb) is quite realistic for a maximum wind of 32 m sec^{-1} (Colón, 1963). The general shapes of the profiles agree well with observations (Fletcher, 1955; Miller, 1963).

The early symmetric period may be summarized as follows. After a short period of development (about 24 hours), a quasi-steady state is reached in which the model storm closely resembles a weak hurricane. The circulation is nearly axisymmetric. Air spirals inward in the low levels, ascends in a narrow ring, and flows outward in the upper levels. The outflow becomes anticyclonic beyond 200 km. However, the absolute vorticity in the outflow layer is positive except in small areas. The central pressure, temperature anomalies, rainfall rates, and the components of the kinetic energy budget are all reasonable for a weak hurricane.

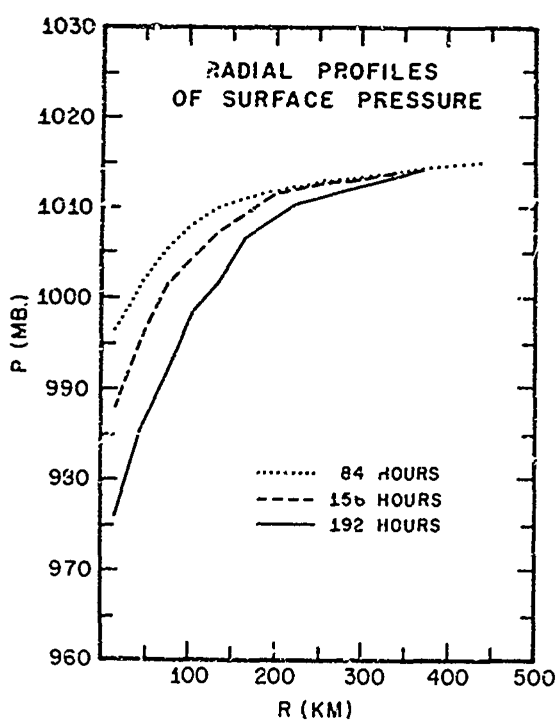


Figure D-6. Radial profiles of surface pressure along an east-west axis at 84, 156, and 192 hours.

ASYMMETRIC STAGE OF THE MODEL

As shown by the central pressure, maximum wind speed, and maximum temperature anomaly (figs. D-3 and D-4), the storm begin a second period of intensification at about 120 hours. The low-level inflow at 156 hours is still fairly symmetric, but shows an increased intensity over that at 84 hours. The maximum wind speed is now 46 m sec^{-1}, hurricane force winds extend outward to 80 km, and gale force winds to 210 km. The average angle of inflow has increased to 38 degrees.

In contrast to the symmetric inflow, the outflow occurs in a highly asymmetric fashion (figs. D-7 and D-8). Outflow occurs in two quadrants, and several small eddies are located about the main center. This asymmetric nature of the outflow is typical of many hurricanes (e.g., Alaka, 1961, 1962; Miller, 1963).

The vorticity at level 3/2 shows large regions of negative absolute vorticity, with minimum values about -30×10^{-5} sec^{-1}. This is in contrast with the vorticity pattern at 84 hours. These regions are transient. They form and reform in various sectors of the outflow level. This unsteady behavior of the outflow is probably related closely to the oscillations in the central pressure and maximum surface wind during the latter portions of the computation (fig. D-2). It is noted that negative absolute vorticity is an observed feature of hurricane outflow (Alaka, 1962) and even appears as a feature of composite mean storms (Izawa, 1964).

The presence of large values of negative absolute vorticity suggests the presence of one or more of the types of dynamic instability discussed in the previous subsection. Since the condition (D.8) refers to symmetric instability and since (D.9) is satisfied in the initial data without noticeable effect, attention was focused on the condition (D.7). The quantity, $2|\vec{V}|/R$, was computed for level 3/2 at 156 hours. In contrast to the early stages, anomalous winds are found to cover substantial areas of the domain and negative values of $2|\vec{V}|/R$ exceed 40×10^{-5} sec^{-1}. The presence of anomalous winds in hurricane outflow has been documented by Alaka (1961).

The role of dynamic instability in the development of tropical cyclones has been subjected to prolonged debate and will not be discussed in detail here. We merely note that the second period of intensification in this model calculation appears to be related to the development of areas of dynamic instability. If we refer to figure D-9, we note that the minimum vorticity in the outflow layer shows a sudden decrease at about 100 hours. The second period of deepening (as measured by central pressure and maximum winds) *follows* this decrease in absolute vorticity by about 20 hours.

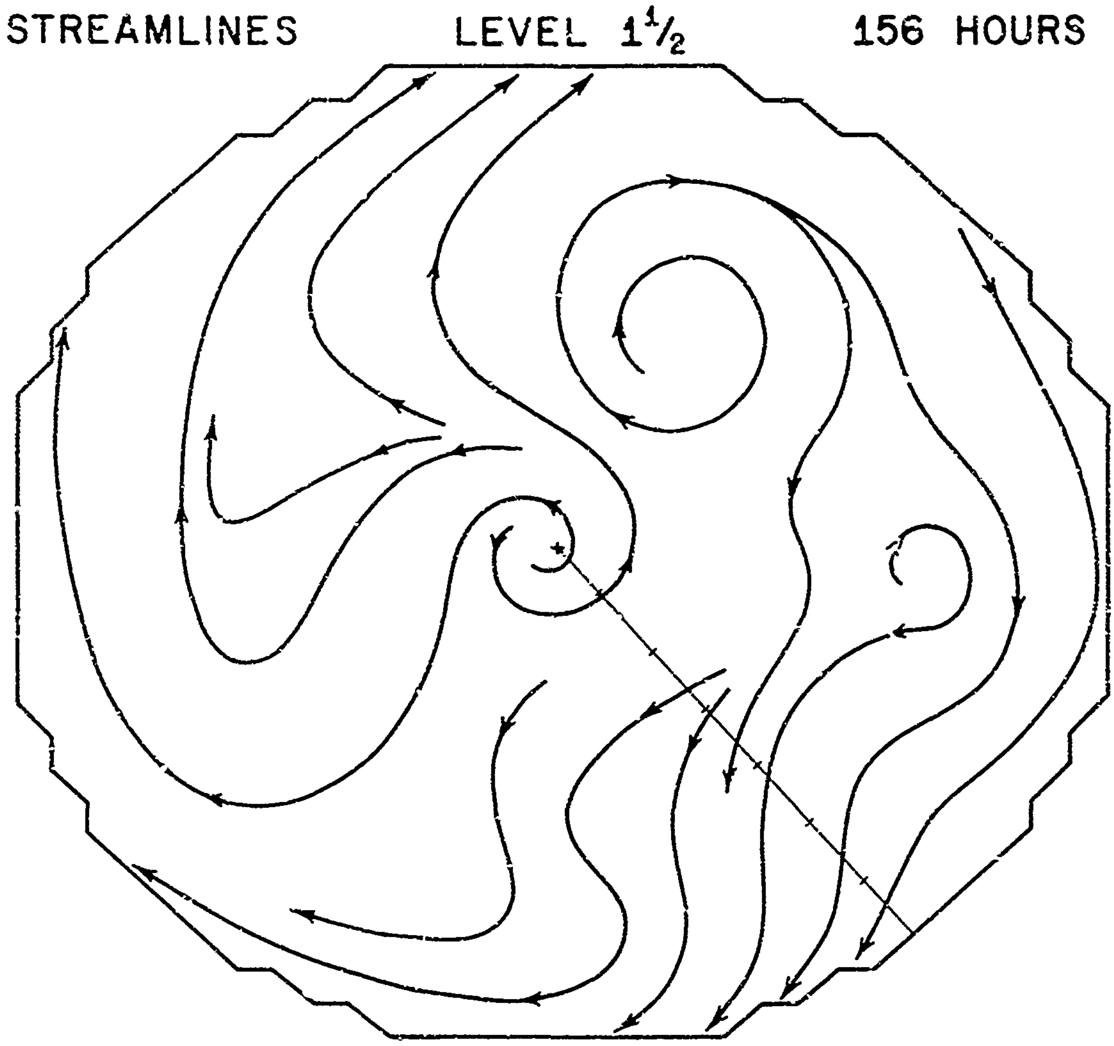


Figure D-7. Streamline analysis for the upper troposphere (level 1½) at 156 hours.

Coincident with the formation of asymmetries in the outflow is the appearance of spiral bands of rising motion which closely resemble hurricane rainbands. The vertical motion pattern at level 3½ (fig. D-9) shows two bands of upward motion which begin at the edge of the domain and spiral inward toward the primary ring of upward motion near the center. The maximum vertical velocity near the center is -440 mb hour^{-1} (about 1.5 m sec^{-1}).

The precipitation pattern, shown in figure D-10, resembles a radar picture of a mature hurricane (e.g., Colón, 1962; Coló et al., 1961). Strong convection occurs near the center in an irregular circle corresponding to an "eyewall."

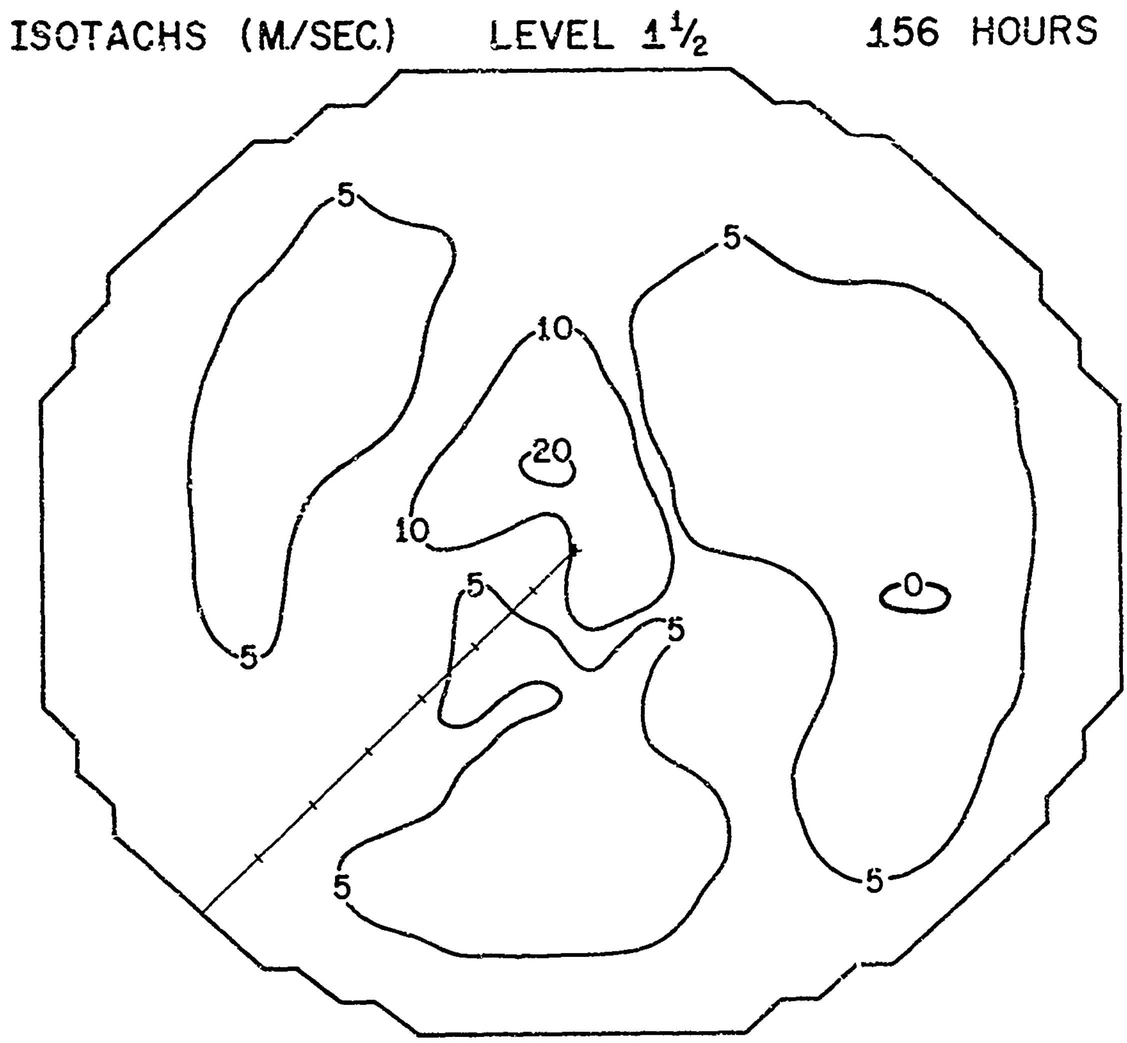


Figure D-8. Isotach analysis for the upper troposphere (level 1½) at 156 hours. Isopheths are labeled in m sec^{-1}.

Maximum rainfall rates in this region are over 100 cm day^{-1}. Two bands of weaker convection spiral in toward the center. The rainfall rates in the spiral bands are much less than those near the center of the storm, averaging only about 3 cm day^{-1}.

The fact that the spiral bands do not appear in the model calculation until the symmetry of the outflow pattern has been destroyed suggests that the generation of the bands and the breakdown of the outflow pattern may be related. As we have noted above, the loss of symmetry in the outflow appears to be associated with dynamic instability. It should

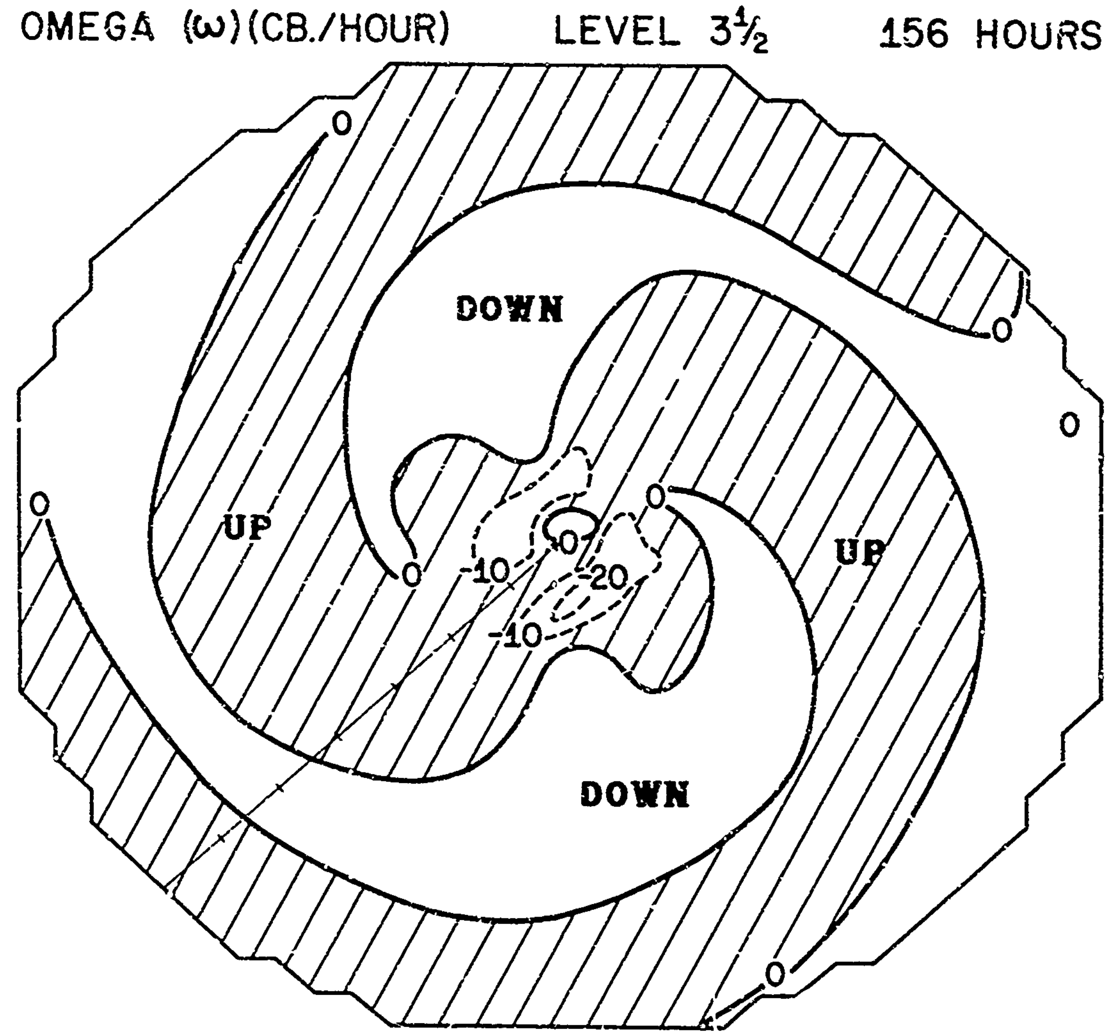


Figure D-9. Individual rate of change of pressure ($\omega = dp/dt$) for level $3\frac{1}{2}$ at 156 hours. Isopleths are labeled in units of cb hour^{-1}.

be emphasized, however, that this linkage is merely speculation at this time and will be pursued further when we have had the opportunity to perform experiments with greater horizontal resolution.

In a recent paper, Anthes (1970) hypothesized that large scale asymmetries between radii of 400 and 1000 km from the hurricane center may play an important role in satisfying the angular momentum budget of the mature hurricane. The mean radial flux of vorticity may be written

$$A \equiv \overline{v_r' \zeta_a'}^{\lambda} + \overline{v_r}^{\lambda} \, \overline{\zeta_a}^{\lambda} \qquad (D.10)$$

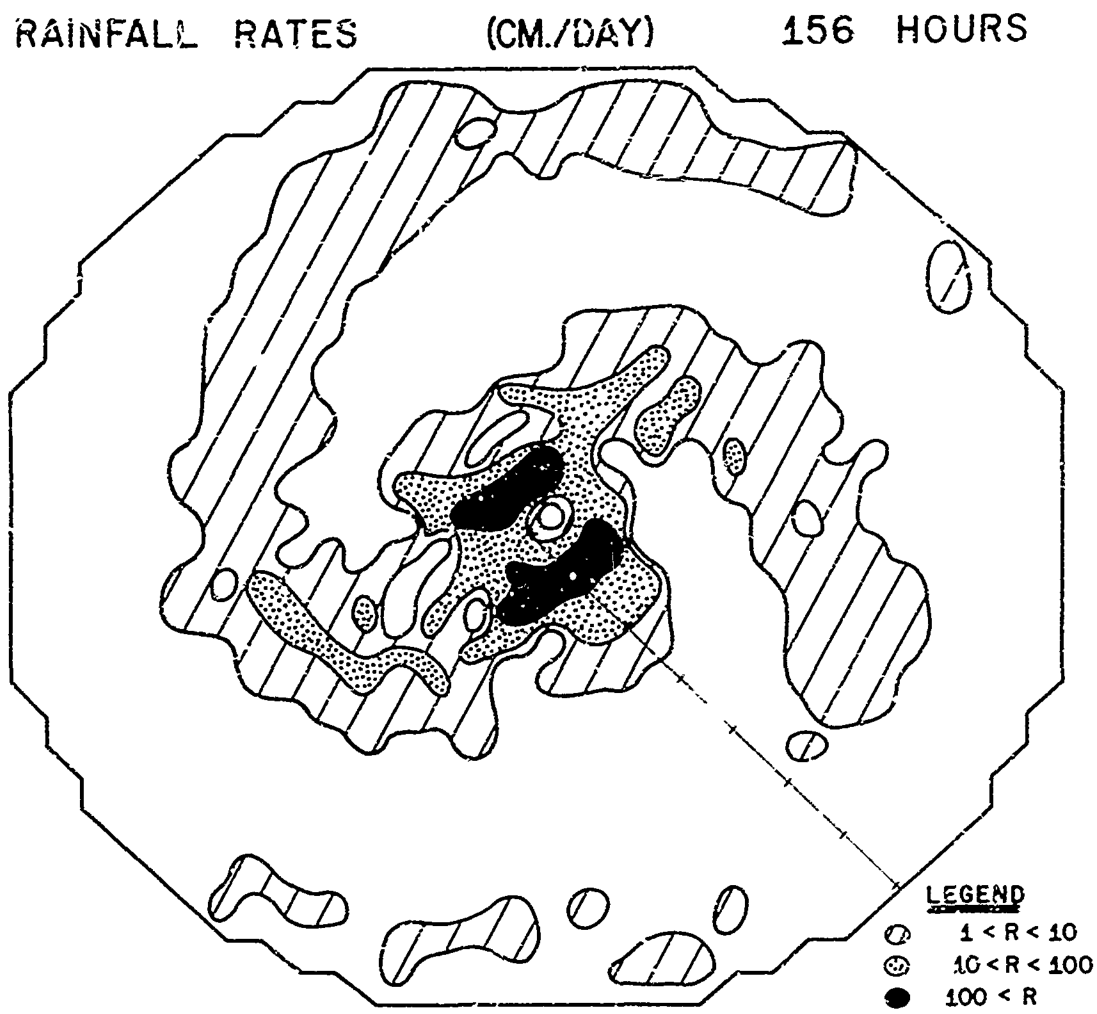


Figure D-10. Rainfall rates (cm day^{-1}) computed from the total release of latent heat at 156 hours. Isopheths are labeled in units of cm day^{-1}.

where the $\overline{(\quad)}^{\lambda}$ operator refers to the azimuthal mean at a given radius and ( )' refers to departures from this mean. Figure D-11 shows the radial profiles of $\overline{v_r' \zeta_a'}^{\lambda}$ and $\overline{v_r}^{\lambda} \overline{\zeta_a}^{\lambda}$ computed for the model storm at 192 hours. Both mean and eddy transports of vorticity are positive inside 200 km. Beyond 200 km, however, where the vertical motion is small, there is a negative correlation between outflow and absolute vorticity, and the eddy flux very nearly balances the mean flux from there to the limit of the domain.

Although the maximum value of $\overline{v_r' \zeta_a'}^{\lambda}$ in figure D-11 is -70×10^{-4} cm sec^{-2}, which is about half the maximum value found by Anthes (1970), the qualitative agreement is good.

Figure D-12 shows the azimuthally averaged vertical cross sections at 156 hours. The mean tangential and radial circulations are more intense than at 84 hours (see fig. D-5). The temperature section shows an increase in mean temperature anomaly from 2.5 to 4.1°C and a reduction in the low-level cold core maximum from -1.5°C to -1.0°C. The weak middle-level cold region located between 105 and 225 km at 84 hours has disappeared by 156 hours.

In summary, beginning at about 100 hours, substantial areas of negative absolute vorticity appear in the upper level and the outflow pattern becomes asymmetric. Rainbands appear during this asymmetric stage. The storm is considerably less steady than during the earlier, symmetric stage, and the central pressure and maximum winds oscillate with a period of about 6 hours. This unsteady behavior appears to be related to the transient behavior of the regions of negative vorticity in the outflow layer.

From the time of appearance of the asymmetries at 120 hours, more or less continuous deepening occurs until the storm reaches a maximum intensity at about 230 hours (see fig. D-3). At this time the storm corresponds to a strong hurricane, with a central pressure of 963 mb and a maximum wind speed of 65 m sec^{-1}. The lapse rate in the inner region is very nearly pseudoadiabatic at this time. After 230 hours, the storm begins to slowly fill and the calculation is terminated at 260 hours.

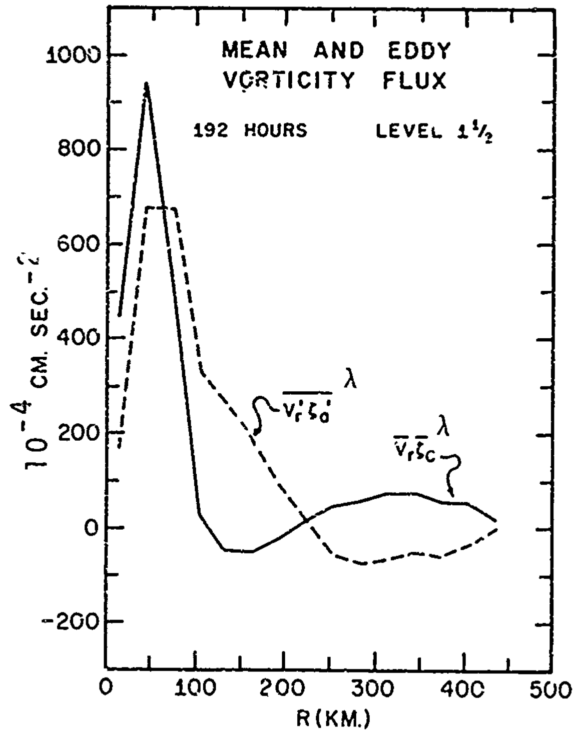


Figure D-11. Azimuthal mean ($\overline{v_r}\ \overline{\zeta_a}^{\lambda}$) *and eddy* ($\overline{v_r' \zeta_a'}^{\lambda}$) *horizontal vorticity flux in the upper troposphere (level 1½) at 192 hours.*

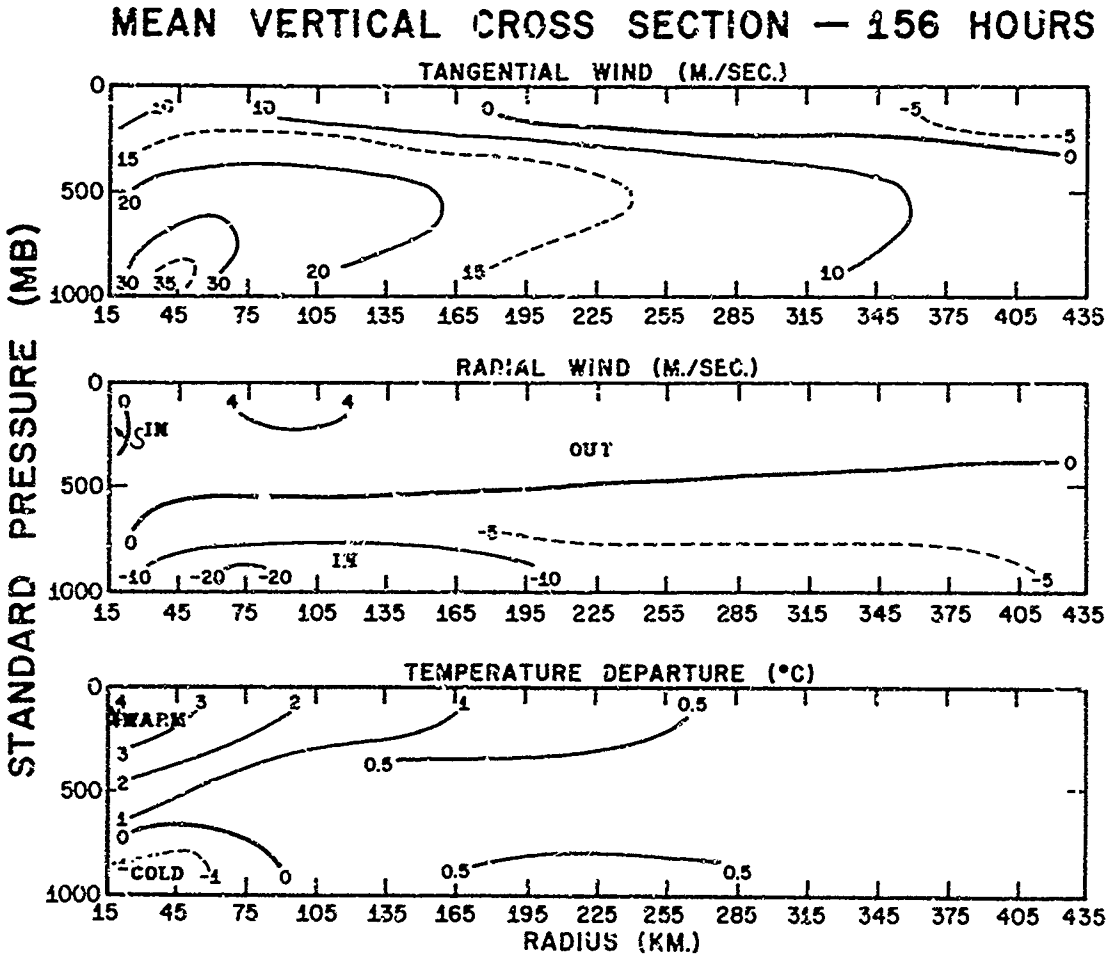


Figure D-12. Azimuthal mean-vertical cross sections for the tangential wind, the radial wind, and the temperature anomally at 156 hours. Isotherms are labeled in °C. Isotachs are labeled in m sec^{-1}.

SUMMARY AND CONCLUSIONS

Preliminary results show that the model is capable of reproducing many observed features of the three-dimensional tropical cyclone. Rather realistic simulations of spiral rainbands and the strongly asymmetric structure of the outflow are obtained.

Despite a relatively coarse horizontal resolution of 30 km, the model produces a storm with maximum winds exceeding 65 m sec^{-1} and a kinetic energy budget which compares favorably with empirical estimates.

In the mature, asymmetric stage of the storm, substantial regions of negative absolute vorticity, anomalous winds, and dynamic instability are present in the upper troposphere. There is a suggestion that the breakdown of the early symmetry of the flow as well as the deepening which takes place during the asymmetric stage are related to the dynamic instability. Large scale, horizontal asymmetries in the outflow are found to play a significant role in the transport of vorticity during the mature stage. Beyond 200 km, the eddy transport of vorticity is opposite in sign and nearly equal in magnitude to the mean transport.

REFERENCES

Alaka, M. A. (1961): The occurrence of anomalous winds and their significance. *National Hurricane Research Project Report No. 45,* U.S. Weather Bureau, Washington, D.C., June, 25 pp.

Alaka, M. A. (1962): On the occurrence of dynamic instability in incipient and developing hurricanes. *National Hurricane Research Project Report No. 50,* U.S. Weather Bureau, Washington, D.C., March, pp. 51-56.

Alaka, M. A. (1963): Instability aspects of hurricane genesis. *National Hurricane Research Project Report No. 64,* U.S. Weather Bureau, Washington, D.C., June, 23 pp.

Anthes, R. A., and D. R. Johnson (1968): Generation of available potential energy in Hurricane Hilda (1964). *Monthly Weather Review, 96,* (5) May, pp. 291-302.

Anthes, R. A. (1970): The role of large-scale asymmetries and internal mixing in computing meridional circulations associated with steady-state hurricanes. *Monthly Weather Review, 98,* (7) July, pp. 521-529.

Anthes, R. A., S. L. Rosenthal, and J. W. Trout (1971): Preliminary results from an asymmetric model of the tropical cyclone. Accepted for publication in the *Monthly Weather Review.*

Anthes, R. A., J. W. Trout, and S. L. Rosenthal (1971): Comparisons of tropical cyclone simulations with and without the assumption of circular symmetry. Accepted for publication in the *Monthly Weather Review.*

Carlson, T. C., and R. C. Sheets (1971): Comparison of draft scale vertical velocities computed from gust probe and conventional data collected by a DC-6 aircraft. Technical Memorandum ERLTM-NHRL No. 91, NOAA, U.S. Dept. of Commerce, Miami, Fla.

Charney, J. G., and A. Eliassen (1964): On the growth of the hurricane depression. *Journal of the Atmospheric Sciences, 21,* (1), January, pp. 68-75.

Colón, J. A., and Staff NHRL (1961): On the structure of Hurricane Daisy, 1958. *National Hurricane Research Project Report No. 46,* U.S. Weather Bureau, Washington, D.C., October, 102 pp.

Colón, J. A. (1962): Changes in the eye properties during the life cycle of tropical hurricanes. *National Hurricane Research Project Report No. 50,* U.S. Weather Bureau, Washington, D.C., March, pp. 341-354.

Colón, J. A. (1963): On the evolution of the wind field during the life cycle of tropical cyclones. *National Hurricane Research Project Report No. 65,* U.S. Weather Bureau, Washington, D.C., November, 36 pp.

Fletcher, R. D. (1955): Computation of maximum surface winds in hurricanes. *Bulletin of the American Meteorological Society, 36,* (6), June, pp. 247-250.

Grammeltvedt, A. (1969): A survey of finite-difference schemes for the primative equations. *Monthly Weather Review, 97,* (5), May, pp. 384-404.

Gray, W. M. (1967): The mutual variation of wind, shear, and baroclinicity in the cumulus convective atmosphere of the hurricane. *Monthly Weather Review, 95,* (5), February, pp. 55-73.

Hawkins, H. F., and D. T. Rubsam (1968): Hurricane Hilda, 1963 II: Structure and budgets of the hurricane on October 1, 1964. *Monthly Weather Review, 96,* (9), September, pp. 617-636.

Izawa, T. (1964): On the mean wind structure of typhoon. *Technical Note No. 2,* Typhoon Research Laboratory, Meteorological Research Institute, Tokyo, Japan, March, 19 pp.

Kuo, H. L. (1965): On formation and intensification of tropical cyclones through latent heat release of cumulus convection. *Journal of the Atmospheric Sciences, 22,* (1), January, pp. 40-63.

Kurihara, Y., and J. L. Holloway (1967): Numerican integration of a nine-level global primitive equation model formulated by the box method. *Monthly Weather Review, 95,* (8), August, pp. 509-530.

Matsuno, T. (1966): Numerical integrations of the primitive equations by a simulated backward difference method. *Journal of the Meteorological Society of Japan, 44,* (1), February, pp. 76-83.

Miller, B. I. (1962): On the momentum and energy balance of Hurricane Helene (1958). *National Hurricane Research Project Report No. 53,* U.S. Weather Bureau, Washington, D.C., April, 19 pp.

Miller, B. I. (1963): On the filling of tropical cyclones over land. *National Hurricane Research Project Report No. 66,* U.S. Weather Bureau, Washington, D.C., December, 82 pp.

Molenkamp, C. R. (1968): Accuracy of finite difference methods applied to the advection equation. *Journal of Applied Meteorology, 7,* (2), April, pp. 160-167.

Ogura, Y. (1964): Frictionally controlled, thermally driven circulations in a circular vortex with application to tropical cyclones. *Journal of the Atmospheric Sciences, 21,* (6), November, pp. 610-621.

Ooyama, K. (1969): Numerical simulation of the life cycle of tropical cyclones. *Journal of the Atmospheric Sciences, 26,* (1), January, pp. 3-40.

Palmén, E., and H. Riehl (1957): Budget of angular momentum and kinetic energy in tropical cyclones. *Journal of Meteorology, 14,* (2), March, pp. 150-159.

Phillips, N. A. (1957): A coordinate system having some special advantages for numerical forecasting. *Journal of Meteorology, 14,* (2), April, pp. 184-185.

Richtmyer, R. D., and K. W. Morton (1967): Difference methods for initial-value problems. Second edition, *Interscience,* New York, 405 pp.

Riehl, H., and J. S. Malkus (1961): Some aspects of Hurricane Daisy, 1958. *Tellus, 13,* (2), May, pp. 181-213.

Rosenthal, S. L. (1969): Numerical experiments with a multi-level primitive equation model designed to simulate the development of tropical cyclones: Experiment I. Technical Memorandum ERLTM-NHRL No. 82, ESSA, U.S. Dept. of Commerce, Miami, Fla., January, 33 pp.

Rosenthal, S. L. (1970): A circularly symmetric, primitive equation model of tropical cyclone development containing an explicit water vapor cycle. *Monthly Weather Review, 98,* (9), September, pp. 643-663.

Smagorinsky, J., S. Manabe, and J. L. Holloway, Jr. (1965): Numerical results from a nine-level general circulation model of the atmosphere. *Monthly Weather Review, 93,* (12), December, pp. 727-768.

Syōno, S., and M. Yamasaki (1966): Stability of symmetrical motions driven by latent heat release by cumulus convection under the existence of surface friction. *Journal of the Meteorological Society of Japan, Ser. 2, 44,* (6), December, pp. 353-375.

Yamasaki, M. (1968a): A tropical cyclone model with parameterized vertical partition of released latent heat. *Journal of the Meteorological Society of Japan, 46,* (3), June, pp. 202-214.

Yamasaki, M. (1968b): Detailed analysis of a tropical cyclone simulated with a 13-layer model. *Papers in Meteorology and Geophysics, 19,* (4), December, pp. 559-585.

APPENDIX E

RESPONSE OF STORMFURY CLOUDLINE CUMULI TO AgI AND AgI·NaI ICE NUCLEI FROM A SOLUTION-COMBUSTION GENERATOR

Edward E. Hindman, II
Navy Weather Research Facility

Shelden D. Elliott, Jr., and William G. Finnegan
Naval Weapons Center

and

Bradley T. Patton
Research Flight Facility

INTRODUCTION

The existing basis for reducing destructive hurricane wind has been the seeding of eyewall cumulus clouds with silver iodide ice nuclei (Simpson and Malkus, 1964; Gentry, 1970). Recent investigations (Woodley, 1970; Gentry, 1971) suggest that less fully developed cumuli at slightly greater distances outward from the present eyewall seeding location may be more responsive to seeding than eyewall cumulus clouds. The responses of such cumuli to silver iodide seedings were studied during the 1970 STORMFURY cloudline operation.

In addition, at the suggestion of Naval Weapons Center, China Lake, California, a special experiment to compare the effectiveness of two different silver iodide solutions was conducted during the 1970 STORMFURY cloudline operation. Silver iodide-sodium iodide-acetone and silver iodide-ammonium iodide-acetone solutions were burned in the solution-combustion generator designed by Patton (1970). Vonnegut (1949, 1950) discovered that combustion products from both solutions were effective ice nuclei. Recent evidence (Finnegan et al., 1971) suggests that the sodium solution produces *complexed* nuclei (AgI·NaI), and the ammonium solution produces *uncomplexed* nuclei (AgI). Laboratory and field evidence (Donnan et al., 1970; Auer and Veal, 1970) have shown that this difference in nucleus structure affects the nucleus activation; the AgI nuclei become active at -5°C and the AgI·NaI nuclei become active at -10°C when both nuclei are released in the warmer-than-freezing regions of cumulus clouds. Furthermore, when both nuclei are released in clouds at -5°C the AgI nuclei are the more active.

PROCEDURE

A NOAA-Research Flight Facility (RFF) DC-6 aircraft was utilized for both seeding the cloudline cumuli and monitoring the effects of seeding. The NOAA-RFF solution-combustion generator (Patton, 1970) was used to produce the ice nuclei (see fig. E-1). The nuclei delivery rate was nearly equivalent to the rate (~1 g sec^{-1}) of the WMU-2 pyrotechnic flares presently used in hurricane seedings.

The cloud response to the nuclei was indicated by simultaneous in-cloud measurements of vertical motions and liquid-water contents (LWC) and ice-water contents (IWC). NOAA-National Hurricane Research Laboratory (NHRL) derived the vertical-motion values from the DC-6 aircraft pitch-angle and

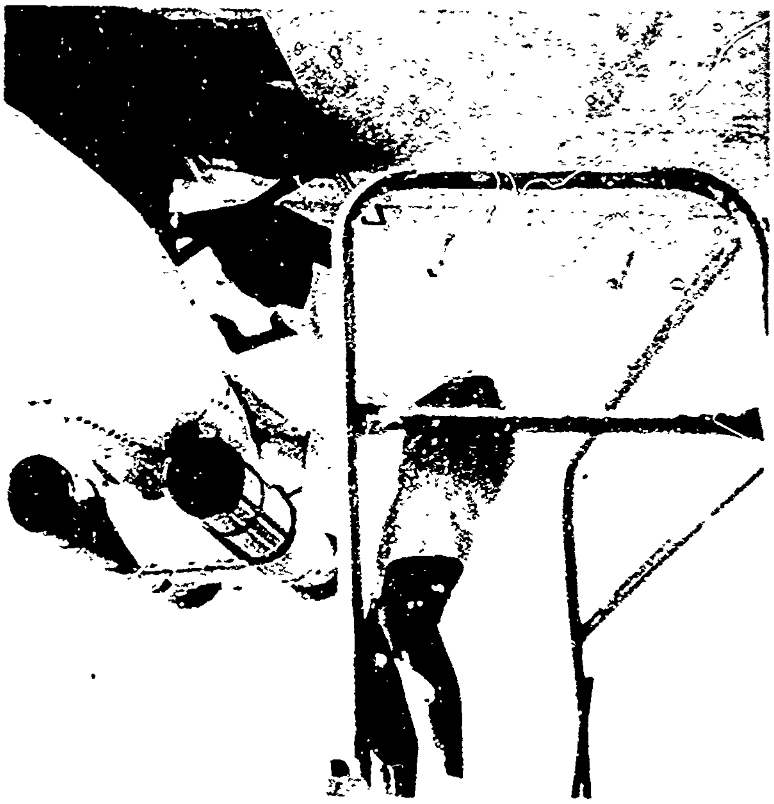


Figure E-1. The NOAA-Research Flight Facility solution-combustion ice nuclei generator is pictured mounted on the NOAA-RFF DC-6 (N8539C). The seeding solution is contained in the tank and the solution is burned in the two cylindrical chambers. The resulting ice nuclei exhaust from the rear of the chambers.

radio-altimeter data (Carlson and Sheets, 1971). The LWC and IWC of the precipitation size particles (dia $\geq$ 200 μm) were determined by Navy Weather Research Facility (WEARSCHFAC) from NOAA-NHRL foil inpactor data (Hindman, 1970)(see fig. E-2). The water contents of the cloud size particles (dia < 200 μm) can be reduced from simultaneously gathered formvar replicator data in a manner similar to the analysis of foil impactor data and will be accomplished at a later data. Results will be described in a subsequent report. These results should provide an important follow-on to previous studies of IWC increases in cumulus clouds that were attributed to seeding (Todd, 1965; Sax, 1969; and Weinstein and Takeuchi, 1970).

Figure E-2. The Meteorology Research, Inc., foil impactor is pictured mounted on the NOAA-RFF DC-C(N8539C). The particle impressions from this impactor are analyzed by Navy Weather Research Facility to produce liquid-water and ice-water contents and liquid and ice particle size-distribution.

The water-content values were computed from particle size-distributions which were reduced from foil impactor data using a CALMA 302 digitizer, a UNIVAC 1107 computer, and a Calcomp plotter. The digitizer was used to code particle sizes and type onto magnetic tapes which were processed on the computer. The resulting water-contents and size-distributions were displayed by means of the plotter. The vertical-motion values were retrived from data cards provided by NOAA-NHRL.

The procedure of seeding and monitoring 1970 STORMFURY cloudline cumuli is illustrated in figure E-3. Seeding was conducted at +5°C in the Cloud I experiment and monitoring penetrations were made at 0 and -5°C, 14 and 27 minutes after seeding, respectively. Immediately following the -5°C monitoring penetration in Cloud I, seeding was conducted on the first -5°C penetration of the Cloud II experiment. Subsequently, two monitoring penetrations were made through Cloud II, both at -5°C at intervals of 15 and 30 minutes after seeding, respectively.

The AgI nuclei were tested on 29 and 30 July, and the AgI·NaI nuclei were tested on 31 July. The procedure outlined in figure E-3 was followed on all 3 days. The flight path in the Cloud I experiment tested the effectiveness of both nuclei when released in the warmer-than-freezing cloud region. The flight path in the Cloud II experiment tested both nuclei when released in the subcooled region of the clouds.

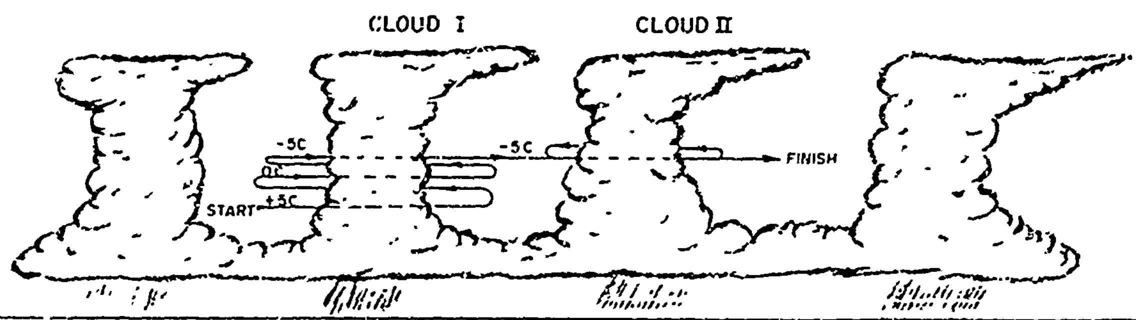


Figure E-3. Procedure for seeding and monitoring STORMFURY cloudline cumuli, 29, 30, 31 July 1970. Seeding was done at +5°C in Cloud I and monitoring passes were made at 0°C and -5°C. Seeding was done on the first pass at -5°C in Cloud II. Two counter-clockwise monitoring passes then were made at -5°C in Cloud II. Cloud I tested warm-cloud release of ice nuclei and Cloud II tested cold-cloud release of ice nuclei.

RESULTS

An example of the average liquid and ice particle size-distributions computed from the foil impactor data gathered in Cloud I is given in figure E-4. The largest particles were ice suggesting that ice particle growth by accretion was more effective than liquid particle growth by coalescence.

Simultaneous foil impactor and vertical-motion data were gathered on each penetration of Cloud I on 29 and 31 July. An example of the water-content and vertical-motion results from these data is presented in figure E-5. The average LWC and IWC for the precipitation size particles (dia ≥ 200 μm) are plotted along with the verticle-motion values. Positive water-content deviations indicate the precipitation core within the cloud. The vertical-motion values are studied to diagnose the extent of the interaction of cloud dynamical and microphysical processes. Similar results from Cloud II are not presented because the analysis of these data has not been completed.

The average LWC and IWC of the precipitation-size particles were computed from the water-content data gathered during the 0°C and -5°C monitoring passes of the Cloud I experiment on 29 and 31 July. The values are presented in table E-1. The IWC was greater than the LWC on all passes.

All precipitation measurements (total, LWC and IWC) were considerably larger on the 29 July Cloud I experiment than in the 31 July experiment.

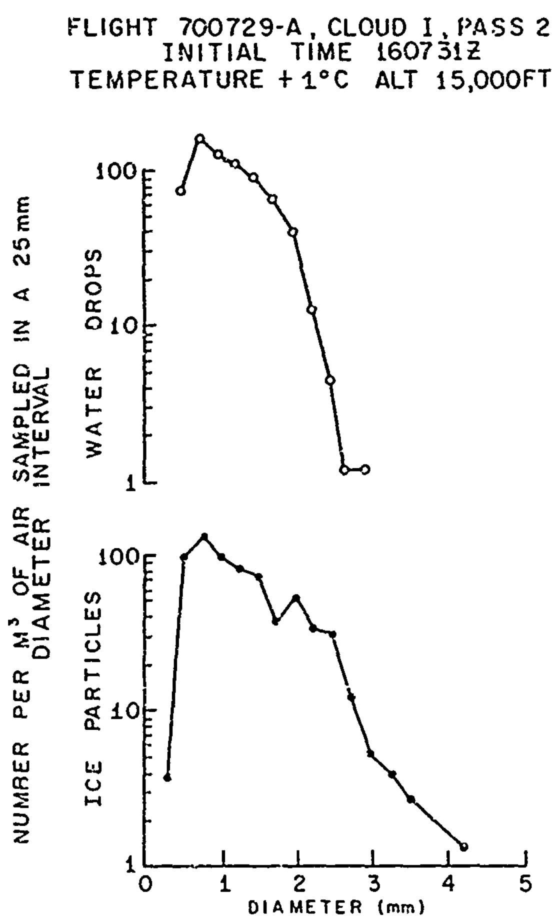


Figure E-4. Liquid and ice particle size-distribution averaged along the 0°C monitoring pass of Cloud I, 29 July 1970 are shown. The unknown particles (u) and small particles (s) contain both ice and liquid particles but are too small to differentiate between either ice or water.

FLIGHT 7700729 A, CLOUD I, PASS 2
INITIAL TIME 160731Z
TEMPERATURE + 1°C ALT. 15,000FT.

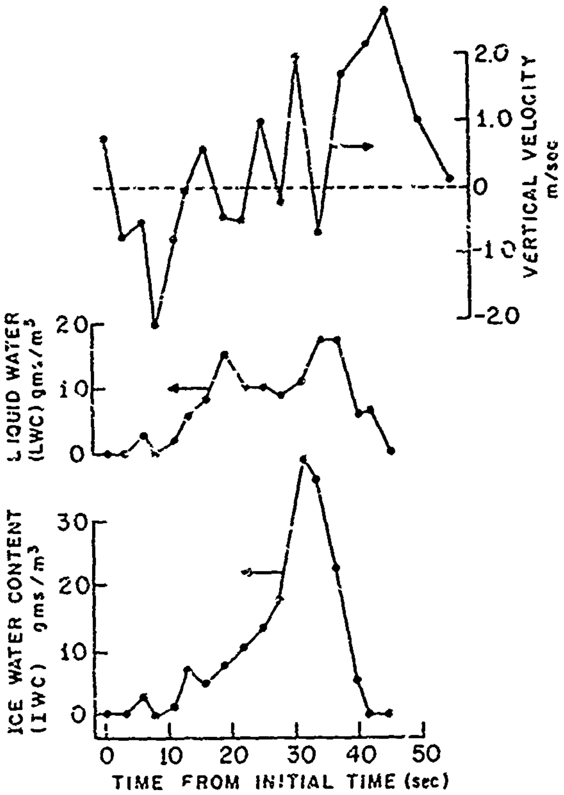


Figure E-5. Navy Weather Research Facility water-content deviations about the average water-content value are plotted with the simultaneously observed NOAA-NHRL vertical-motion values. The data are from the 0°C monitoring-pass of Cloud I on 29 July 1970. The initial time is the time the aircraft entered the cloud. The aircraft flew at 100 m sec^{-1}; as a result, 10 sec on the time equals 1 km. The average LWC and IWC values are 0.715 and 0.958 g m^{-3}, respectively.

On both days, however, the absolute precipitation amounts (total, LWC and IWC) at the lower level (0°C) were from five fold to an order of magnitude greater than at the upper level (-5°C), and the percentage of liquid content with respect to ice content was greater at the lower level. These figures indicate that the layer between 0°C and -5°C was an active precipitation formation region and that the increases in both the LWC and the IWC between -5°C and 0°C may indicate significant contributions from both coalescence and accretion.

The ratio of the LWC to the IWC at the 0°C level was approximately the same on both days but was somewhat lower at the -5°C level for the AgI experiment, suggesting effects of seeding which will be discussed in more detail.

While these results are quite useful, their reanalysis in conjunction with cloud particle distributions from the formvar replicator data should contribute to improved understanding and improved parameterization of microphysical processes in numerical simulation models.

Table E-1. Average Liquid-Water and Ice-Water Content of Precipitation ($g\ m^{-3}$).

Test Day	Nuclei	CLOUD I Experiment* Monitoring Level 0°C LWC	IWC	LWC/IWC	-5°C LWC	IWC	LWC/IWC
29 July 1970	AgI	0.715	0.958	0.75	0.074	0.188	0.39
31 July 1970	AgI•NaI	0.078	0.106	0.74	0.010	0.022	0.45

* Cloud II Experiment data not reduced yet

The average vertical motions were computed and the maximum updrafts were isolated from the vertical-motion data gathered on all passes in the Cloud I and Cloud II experiments on 29 and 31 July. The values are presented in table E-2. The maximum positive vertical-motion and updrafts for all passes occurred during the seeding pass and then tapered off during the monitoring passes.

Table E-2. Observed Average Vertical Motion/Observed Maximum Updrafts ($m\ sec^{-1}$).

Test Day	Nuclei	Experiment CLOUD I Seed +5°C	CLOUD I Monitor 0°C	CLOUD I Monitor -5°C	CLOUD II Seed -5°C	CLOUD II Monitor -5°C	CLOUD II Monitor -5°C
29 July 1970	AgI	3.0/ 9.3	0.5/ 3.5	1.0/ 4.0	1.0/ 6.2	0.3/ 2.6	0.8/ 4.0
31 July 1970	AgI•NaI	1.5/ 7.5	0.7/ 5.2	0.2/ 2.5	2.7/ 8.2	2.7/ 5.7	-0.3/ 2.1

DISCUSSION

Cloud I contained an average maximum updraft of 5 m sec^{-1} (averaged from table E-2) on both 29 and 31 July. Assuming a majority of the ice nuclei were transported in this updraft, the nuclei would have reached the 0°C level, the -5°C level, and the -10°C level in 3 minutes, 7 minutes, and 10 minutes, respectively, after the seeding time. The DC-6

aircraft reached the 0° and -5° levels 14 and 27 minutes after seeding, respectively. Hence, it is likely that most of the seeding material had been carried up and through these levels prior to the aircraft penetration.

The precipitation resulting from seeding, however, may have been observed at the -5°C level in Cloud I on 29 July. The median mass diameter of the ice precipitation particles observed at -5°C was approximately 1.5 mm. These ice particles were estimated to grow from ice nuclei to 1.5 mm in 17 minutes in the observed in-cloud conditions (-5°C, 1 g m^{-3} LWC) (Hindman and Johnson, 1970). The particles' fall velocity after 17 minutes of growth was estimated to be faster than the updraft, thus permitting the particles to settle from the rising seeding region. Assuming that a majority of AgI nuclei are activated in 3 minutes after the seeded region passed -5°C, then the total time from seeding to grow 1.5 mm ice particles is 7 min + 3 min + 17 min = 27 minutes which is the time it took the aircraft to reach the -5°C level.

The LWC/IWC ratio illustrated in table E-1 shows that the 0°C passes in Cloud I on 29 and 31 July had similar LWC/IWC ratios. The -5°C passes, however (which presumably measure the seeding effects on the precipitation), had a lower ratio on the 29th (0.39) than on the 31st (0.45). The higher relative ice content of the AgI-seeded cloud (29th) at -5°C compared to that of the AgI·NaI-seeded cloud (31st) suggests that the aircraft may have intercepted the ice precipitation particles settling from the region of the cloud affected by the AgI.

Random interpretation error of approximately ±19 percent has been estimated when differentiating between ice and water particle impressions from the foil sampler. The difference in the LWC/IWC ratio is slightly greater than the possible random error, therefore the difference is considered real.

It would not be expected that the ice precipitation settling from the region of Cloud I affected by the AgI·NaI would be intercepted. These particles formed at and below -10°C and probably did not overcome the updraft to reach the -5°C level in the 27-minute interval between seeding and the monitoring passes. Simpson (1970) recently showed that precipitation assumed to result from seeding was observed on radar within 10 minutes at 6 km below the seeded region. This remarkably short period of time was possible because a 4 m sec^{-1} downdraft assisted the precipitation in falling from the formation level (6-7 km above cloud base) to the observation level (1 km above cloud base).

Significant decreases in the average vertical motion after seeding were measured in both the AgI and AgI·NaI experiments in Cloud II (see table E-2). An unexpected reduction was registered in the AgI-seeded cloud on the first monitoring pass followed by a restoration trend on the second monitoring pass. In contrast, the AgI·NaI-seeded cloud showed a slight decrease during the first monitoring pass but a more significant reduction during the second monitoring pass.

Admittedly the vertical motion values constitute a limited sample and the magnitudes are near the data's noise level. If these observations are considered somewhat credible, they still present a paradox and suggest certain weaknesses in current parcel and bubble theories of convection. The theories may not adequately explain the paradoxical decrease in updrafts following seeding. A more rigorous application of the hydrodynamic and thermodynamic equations integrated with a more realistic microphysical parameterization may be required for adequate simulation of cumulus convective processes. Such a formulation is currently being considered at WEARSCHFAC which would explain the sequence of events in the Cloud II experiments according to the suggested processes below.

For both seedings in Cloud II, the average vertical velocities were measured below the region in which the artificial nuclei increased natural glaciation. The decreases in updrafts following these seedings suggest that the initial effects of seeding decrease the stability and increase the updrafts in and above the increased glaciation region while increasing the stability and suppressing the updrafts below this region. In the AgI experiment the increased release of the latent heat of fusion would take place directly above the seeding and sensing levels because these nuclei become active at -5°C. Hence the suppressing effects on the updrafts would be noticed rather quickly. Such was the case on the first monitoring penetration, and perhaps the effect began to diminish by the time of the second pass because the updrafts increased. In the AgI·NaI experiment, the increased release of the latent heat of fusion would take place at higher levels than in the AgI experiment because the AgI·NaI are less active than the AgI nuclei. The impact on the updrafts would be delayed, which is consistent with the trend of values shown in the Cloud II experiment in table E-2.

These processes suggest the following cycle of events which may occur after a cumulus cloud is seeded:

a. The seeding material will be carried upward with increased glaciation taking place at the level according to the activation of the seeding material

and will be followed by increased condensation and increased precipitation.

b. Initially, the increased release of latent heat will augment the updrafts in and above the increased glaciation level and suppress updrafts below this level.

c. Subsequently, the net effect of the whole process will warm the cloud core as well as create a divergent outflow in the upper levels. The warming and outflow will decrease the surface pressure which will cause an increased inflow at the lower levels and produce a general increase in upward motion throughout the cloud.

This cycle suggests prospects of developing a rationale for increasing cloud growth by successive pulsed seedings. Empirical evidence compiled by St. Amand (1969) indicates that pulsed seedings may increase cloud growth and merge individual clouds into cloud systems. While the cycle is not properly reflected in current simple cloud models, its physical reasoning is qualitatively consistent.

An advantage of glaciating tropical cumuli with AgI ice nuclei rather than AgI•NaI ice nuclei is illustrated in figure E-6. Illustrated are cloud vertical motions that were simulated with a numerical cumulus model described by Matthews in this report (app. H). The vertical motions decrease to zero at 6.3 km for the natural cloud assumed to glaciate at -25°C, indicating a cloud top at 6.3 km. The cloud seeded with AgI•NaI ice nuclei also did not grow more than 6.3 km. The cloud reached the -6°C level but needed to grow to roughly the -10°C level before the AgI•NaI ice nuclei would increase natural glaciation and increase cloud growth. The cloud seeded with AgI ice nuclei, however, grew to 11 km because these nuclei increased natural glaciation at the -5°C level. This glaciation boosted the cloud past the 6.3 km level it would have grown to naturally.

CONCLUSIONS

Ice-water content data and vertical-motion data from two cloudline cumuli seeded with AgI ice nuclei tentatively indicate that the cumuli began to glaciate at approximately -5°C. Similar data from two other cloudline cumuli seeded with AgI•NaI indicate that the cumuli began to glaciate at a colder temperature, possibly -10°C. These tentative conclusions are in agreement with previous laboratory results

Donnan et al. (1970) and field results of Auer and Veal (1970). This agreement suggests that given a choice of acetone solutions to burn in a solution-combustion generator, the AgI-NH_4-acetone solution would be the choice if glaciation at temperatures near -5°C is desired.

Vertical-motion data from two cloudline cumuli seeded and monitored at the -5°C level suggest that the initial effects of seeding may have suppressed the updrafts below the regions of increased glaciation and heating

Further testing, however, is needed to confirm these preliminary conclusions. The extremely limited number of seeded clouds prevented a statistically significant sample. Furthermore, the lack of control clouds prevented objective comparisons of the seeded clouds with those developing naturally.

The operational data gathered from the NOAA-RFF solution-combustion generator indicated that the device can be used routinely to seed STORMFURY cloudline cumuli.

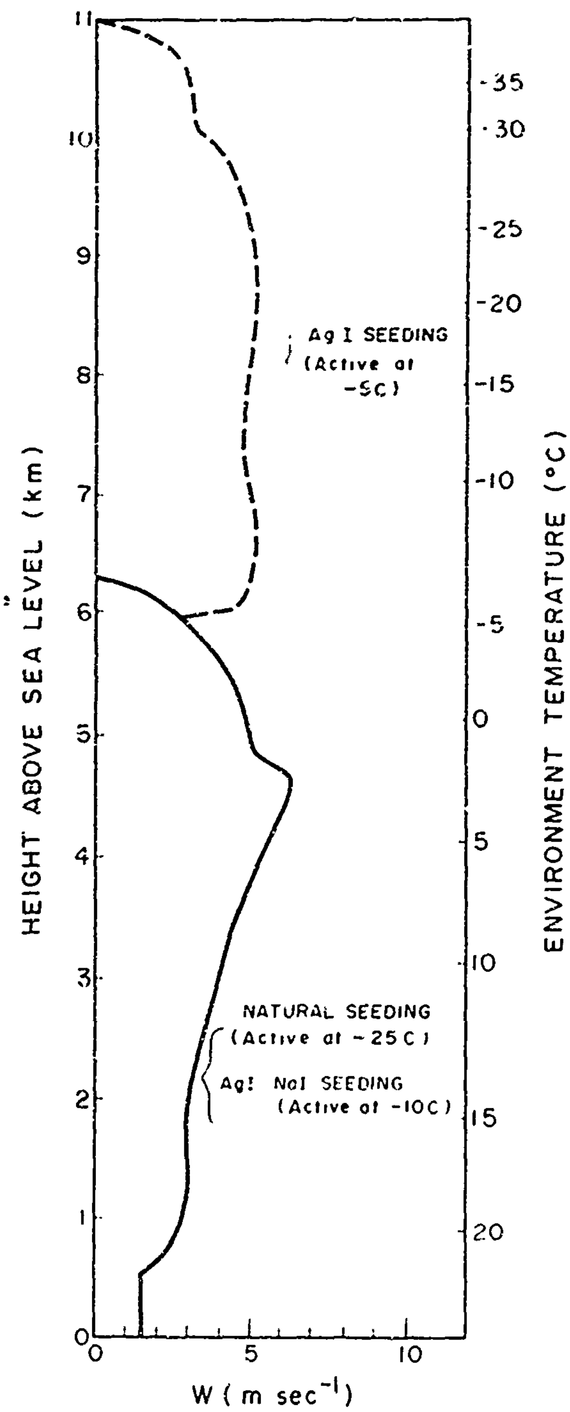


Figure E-6. Effect of seeding on updrafts in a cumulus cloud in a hurricane environment, as simulated by Matthews (1971) using a one-dimensional cumulus model. Cloud base diameter was assumed to be 3 km. The atmospheric sounding, from which cloud growth was simulated, was from the 996-999 mb pressure region of a hurricane.

RECOMMENDATIONS

1. Conclusions derived from the evaluation of 1970 STORMFURY cloudline data presented in the report are limited by the preliminary nature of the experiments. Subsequent experiments should be more extensive to determine if the initial effect of seeding tropical cloudline cumuli is the suppression of updrafts.

2. The need for shorter time-separation between seeding and monitoring passes and the need for monitoring passes above the seeding level suggest a dual-aircraft experiment.

3. The difficulty in executing monitoring passes in rapid succession and monitoring passes above the seeding level indicates the desirability of having an aircraft that can stay within the core and rise at approximately the same speed as the seeded updraft. The cloud physics instrumented NCAR SGS 2-32 sailplane (Schribner, 1966) is suited for these flight requirements. This aircraft would be able to seed the core of the rising air and continuously monitor the seeding effects. Results from such flights would illustrate how thoroughly the seeding is glaciating the available supercooled water and provide a measure of the effects of seeding on vertical accelerations. These results should contribute to a much needed improvement in the parameterization of seeding effects in numerical cloud models.

REFERENCES

Auer, A. H., Jr. and D. Veal (1970): Evaluation of cloud seeding devices in an outdoor laboratory. *Project Report, Naval Weapons Center Contract N66001-70-C-0639*, November, (on file, Naval Weapons Center (code 602), China Lake, California).

Carlson, T. N., and R. C. Sheets (1971): Comparison of draft scale vertical velocities computed from gust probe and conventional data collected by a DC-6 aircraft. Technical Memorandum ERLTM-NHRL No. 91, NOAA, Dept. of Commerce, NHRL, Miami, Fla.

Donnan, J. A., D. N. Blair, W. G. Finnegan and P. St. Amand (1970): Nucleation efficiencies of AgI-NH_4I and AgI-NaI-Acetone solutions and pyrotechnic generators as a function of LWC and generator flame temperature. A Preliminary Report. *The Journal of Weather Modification, 2*, pp. 155-164.

Finnegan, W. G., P. St. Amand and L. A. Burkardt (1971): An evaluation of ice nuclei generator systems. Submitted to *Science*.

Gentry, R. C. (1970): Hurricane Debbie modification experiments, August 1969. *Science, 164*, pp. 473-475.

Gentry, R. C. (1971): Progress on hurricane modification research-October 1969 to October 1970. Presented at *Twelfth Interagency Conference on Weather Modification*, October 28-30, Virginia Beach, Va.

Hindman, E. E., II (1970): Cloud particle samples and water contents from a 1969 STORMFURY cloudline cumulus. *Project STORMFURY Annual Report 1969*, U.S. Dept. of Navy and U.S. Dept. of Commerce, Appendix F.

Hindman, E. E., II and D. B. Johnson (1970): Numerical simulation of ice hydrometeor development. Preprints - *Conference on Cloud Physics*. American Meteorological Society, Boston, Mass., pp. 63-64.

Patton, B. T. (1970): Preliminary report on the Patton mark series generators. On file at NOAA-RFF, Miami, Fla., 5 pp.

Sax, R. I. (1969): The importance of natural glaciation of the modification of tropical maritime cumuli by silver iodide seeding. *Journal of Applied Meteorology, 8*, pp. 92-104.

Schribner, K. (1966): The explorer. *Journal Soaring Society of America*, pp. 12-13.

Simpson, J. (1970): On the radar-measured increase in precipitation within ten minutes following seeding. *Journal of Applied Meteorology, 9*, pp. 318-320.

Simpson, R. H., and J. S. Malkus (1964): Experiments in hurricane modification. *Scientific American, 211*, p. 27.

St. Amand, P. (1969): Weather modification techniques development. Appears in "A Summary of the U.S. Navy Program and FY-1969 Progress in Weather Modification and Control." *WEARSCHFAC Technical Paper No. 20-69*, pp. 38-39.

Todd, C. J. (1965): Ice crystal development in a seeded cumulus cloud. *Journal of Atmospheric Science, 4*, pp. 70-78.

Vonnegut, B. (1949): Nucleation of supercooled water clouds by silver iodide smokes. *Chemical Review, 44*, pp. 277-289.

Vonnegut, B. (1950): Techniques for generating silver iodide smoke. *Journal of Colloid. Sciences, 5*, p. 377.

Weinstein, A. I., and D. M. Takeuchi (1970): Observation of ice crystals in a cumulus cloud seeded by vertical-fall pyrotechnics. *Journal of Applied Meteorology, 9*, pp. 265-268.

Woodley, W. L. (1970): Precipitation results from a pyrotechnic cumulus seeding experiment. *Journal of Applied Meteorology, 9*, pp. 242-257.

APPENDIX F

MEASUREMENTS OF VERTICAL MOTION IN THE EYEWALL CLOUD REGION OF HURRICANE DEBBIE

Toby N. Carlson
National Hurricane Research Laboratory

INTRODUCTION

Vertical motions on a cumulus cloud scale (1 to 100 km) can be estimated using various parameters recorded by the RFF DC-6 aircraft (Carlson and Sheets, 1971). The formula used to obtain the drift scale vertical velocity, W, is

$$W = V_t (\alpha_d - \theta_d) + W_p \text{ ,} \qquad \text{(F.1)}$$

where V_t is the true air speed, α_d and θ_d are the angle of attack and pitch angle of the aircraft with respect to the equilibrium values of these angles, and W_p is the aircraft vertical velocity. In the DC-6 aircraft, the latter is determined by differentiating the radio-altimeter values to give change in aircraft height with time. The true airspeed and pitch angle are directly measured; the equilibrium value of the pitch angle must be continuously determined since it is found to drift slowly with time.

The equilibrium pitch angle, θ_e, is determined by assuming that the mean vertical motion throughout a given straight line pass is zero for short passes through cumulus clouds; in longer passes, such as straight line radial legs through hurricanes, it is assumed that W is zero when averaged over a longer interval, L, (~50 to 75 miles); a variable θ_e is thereby determined at the mid-point of a sliding scale of length L which will be shorter than the length of the pass. Inspection of the vertical motion trace may indicate that the vertical velocity averaged over L need not be zero, in which case the zero vertical velocity axis should be adjusted by eye; for example, if the values fail to approach zero in the undisturbed environment of a cumulus cloud or in the center of the hurricane eye. The angle of attack is not measured but is computed indirectly from the equation of motion for aircraft lift. In practice during flights in hurricanes,

the basic 1 sec digital values are converted to a 6 sec block average in order to minimize noise in the data. For cumulus clouds, a weighted 4 sec (binomially smoothed) running mean is used.

PROFILE OF VERTICAL MOTION IN HURRICANE DEBBIE (1969)

The draft scale vertical motion computations were determined for all radial legs in Hurricane Debbie on 18 and 20 August 1969, by the 39-C DC-6 aircraft which was the only aircraft capable of making such measurements on those occasions. Of the 10 radial penetrations made on the 20th, and of seven made on the 18th by this aircraft a total of eight and five passes, respectively, were made along a southwest-northeast azimuth. Most of the penetrations began and ended about 70 km from the center and all of them penetrated both of the eyewalls and the inner clear region of the eye.

Examination of the individual vertical motion profiles showed that there was considerable variability from pass to pass due to the rapidly shifting echo patterns. In order to arrive at a composite picture for the storm, the vertical motion profiles for the southwest-northeast legs were arithmetically averaged together for the eight passes on the 20th and the five passes on the 18th. Each radial leg from the eye was averaged with respect to the point of entry of the aircraft into (or from) the eyewall cloud from (or into) the clear eye. Except for the outer portions of the eyewall cloud region in figure F-1 where there were fewer observations, the composite profiles of vertical motion represent an average of eight or five points, respectively, for the 20th and 18th. (The inner portion of the clear eye was composited separately and is not shown here.)

Both profiles show some similarity in that a broad domain of rising motion is found in the eyewall cloud region which is surrounded by a more narrow ring of descending (or nearly neutral) vertical motion near the eyewall (and just inside the eye) and also on the outer edges of the wall cloud region. The strength of the updrafts appeared to be about the same on the 18th as on the 20th, although the storm had deepened appreciably in the interval. In figure F-1, the maximum ascent was 2-3 m sec^{-1} (strongest in the southwest sector), while the mean rising motion averaged over the rising annulus was about 1 m sec^{-1} on both days. Because the vertical motion measurements were made from a series of passes which span ed only a few hours, it is difficult to

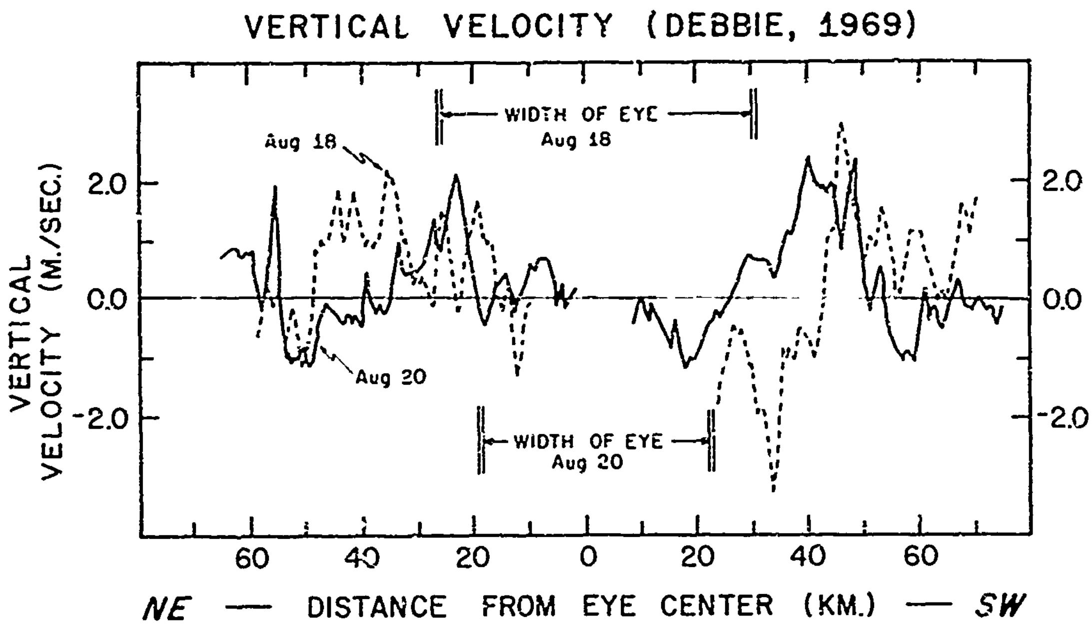


Figure F-1. Composited vertical velocity profile for Hurricane Debbie as determined from the RFF 39-C DC-6 aircraft. The profile represents an average of 8 radial legs on 20 August 1969, and 5 radial legs on 18 August, which were on a northeast-southwest azimuth. Compositing was done with respect to the inner face of the eyewall cloud, the mean positions of which are indicated by the width of the eye.

assess the effects of seeding on the updraft profile in Hurricane Debbie. The composite profiles, however, demonstrate the possible use of vertical motions in evaluating seeding experiments (see app. E in this report).

ACCURACY OF THE VERTICAL MOTIONS

Carlson and Sheets (1971) have discussed deficiencies in the measurement of draft scale vertical motion and the accuracy of the calculations, based on a comparison with simultaneous measurements made with the RFF gust probe system in a series of test passes through individual cumulus clouds. Their results indicate that the measurement accuracy depends on the scale in question and on the intensity of the turbulent motions (the variance of W). Reliability of the measurements is considered to be greatest for updrafts on the scale of the cumulus cloud (1 to 10 km) and for strong vertical motions.

But for scales of motion a kilometer or less, the uncertainty decreases rapidly with decreasing wavelength of the updraft. A possible noise frequency (that of aircraft oscillation) may exist with a frequency of 5-10 sec and an amplitude of about 0.5 m sec^{-1}. Absolute errors appear to increase with increasing intensity of the vertical motions, but the percent error in a particular draft profile decreases with the amplitude of the draft, and the uncertainty is probably a small fraction of the amplitude value when the peak value exceeds a few meters per second. Conversely, the percentage error for a particular updraft or downdraft profile decreases with increasingly weaker vertical motions and may become comparable to the amplitude of the motions themselves in weak cumulus or in clear air where the maximum draft speeds are a meter per second or less. A minimum uncertainty of 0.4-0.8 m sec^{-1} may be present even in clear air where the vertical velocity variance is of this order. In composites such as the one shown for Debbie (fig. F-1), the noise may be canceled to some extent; therefore, the magnitude of the broad profile of updrafts and downdrafts may have more significance than it would have had in an individual pass.

Vertical motions are also adversely affected by sharp turns and during significant changes in aircraft altitude brought about by the pilot attempting to climb or descend. For that reason the calculations are felt to have some validity only in straight line (or radial) passes flown at a constant level where the power setting changes by the pilot are kept to a minimum. Occasional power setting changes, which are necessarily made by the pilot in penetrating intense cumulus updrafts of the eyewall cloud of a hurricane, are detrimental to the measurements but are not considered to be critical in determining the basic draft profile. Power setting changes are also made during cloud seeding runs when the silver iodide burner is operated on board the DC-6 aircraft. In the future, an angle of attack vane will be mounted on the aircraft which will hopefully improve the measurements of vertical velocity since, at present, α_d is not accurately known.

REFERENCE

Carlson, T. N., and R. C. Sheets (1971): Comparison of draft scale vertical velocities computed from gust probe and conventional data collected by a DC-6 aircraft. Technical Memorandum ERLTM-NHRL No. 91, NOAA, Dept. of Commerce, NHRL, Miami, Fla.

APPENDIX G

AN ESTIMATE OF THE FRACTION ICE IN TROPICAL STORMS

W. D. Scott and C. K. Dossett
National Hurricane Research Laboratory

INTRODUCTION

With the present concept of the modification of tropical storms, a considerable amount of supercooled water must exist above the freezing level in the storm cloud system. This thinking precludes modification of the storm if the supercooled water has already frozen and turned to ice. Hence, an estimate of the ice content of the clouds at levels between 0° and -20°C would help us assess the probability of being able to modify the storm, and, perhaps, give an *a posteriori* judgment on the success of a seeding mission.

We currently have acquired three instruments that should give an estimate of ice concentration during a flight into a storm. These are the foil impactor, the continuous particle replicator, and the ice particle counter. The foil impactor has been described in previous STORMFURY Reports (see Sheets, 1969; Hindman, 1970) and some data from the cloud-line experiments are presented in this report by Hindman (app. E). The particles are impacted on a strip of aluminum foil and the size and character of the particles are derived from the impressions they make.

The ice particle counter was recently acquired through a contract with Mee Industries, Altadena, California. It uses an optical technique which measures the scintillations or "twinkles" ice crystals make when they reflect light off their secular faces. It is now undergoing calibration tests, but preliminary test results indicate that it can count ice particles in real time with a 75 percent or better reliability even in the worst case when large water drops are present in the sample.

The continuous particle (formvar) replicator is a device which captures cloud particles (i.e., droplets, raindrops, and ice crystals) and forms plastic replicas of them on a 16-mm motion picture film. The device currently in operation was also manufactured by Mee Industries. Its essential features are nearly identical to the instrument manufactured by

Meteorology Research, Inc., and described by Sheets (1969); the instrument and its basic principles have been used for years, and several different versions of it are presently being used (see for example: MacCready and Todd, 1964; Spyers-Duran and Braham, 1967; Ruskin, 1967; Patrick and Gagin, 1971). It has several deficiencies, but it does seem reasonable that the instrument can be used to obtain a subjective estimate of the fraction ice in clouds, i.e., that fraction of the total hydrometeor population considered to be ice. With the continued operation of the instrument in hurricanes and tropical storms, a large quantity of in-cloud data has been amassed. In this report some of the more recent data are considered, and the fraction ice at different levels in these storms estimated.

THE FLIGHT TRACKS

The aircraft flight tracks on which the data were taken are presented in figures G-1a, G-1b, and G-1c and are represented by arrows. On figures G-1a and G-1b the orientation and the relative locations of the clouds are preserved;

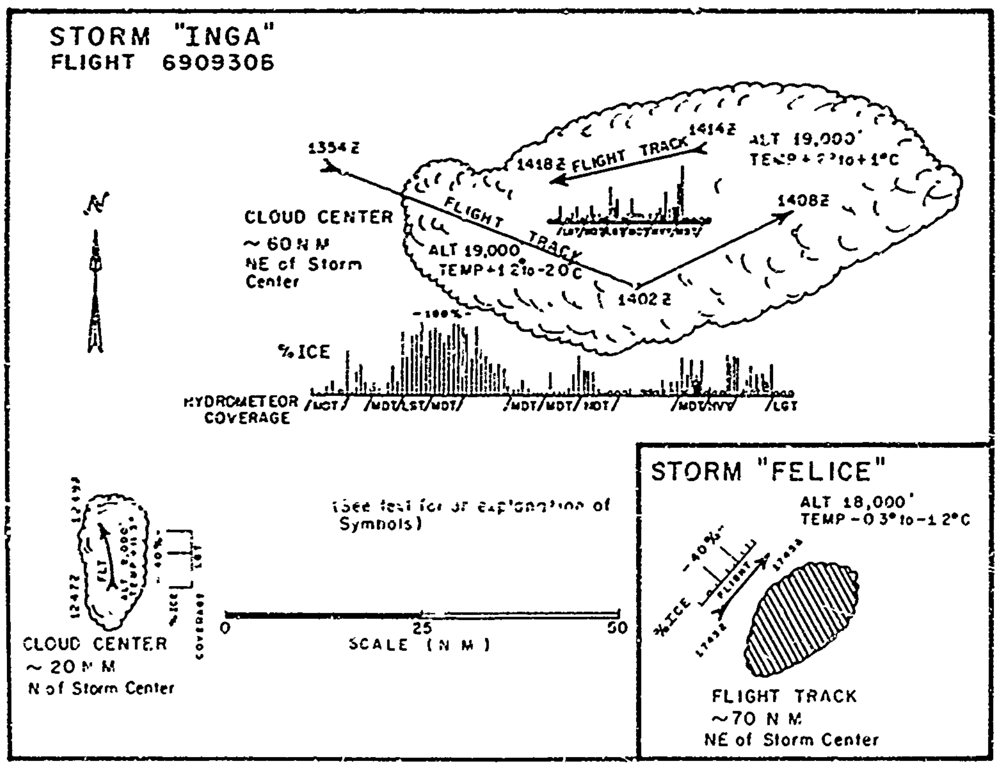


Figure G-1a. Sampling locations in Tropical Storms "Inga" and "Felice."

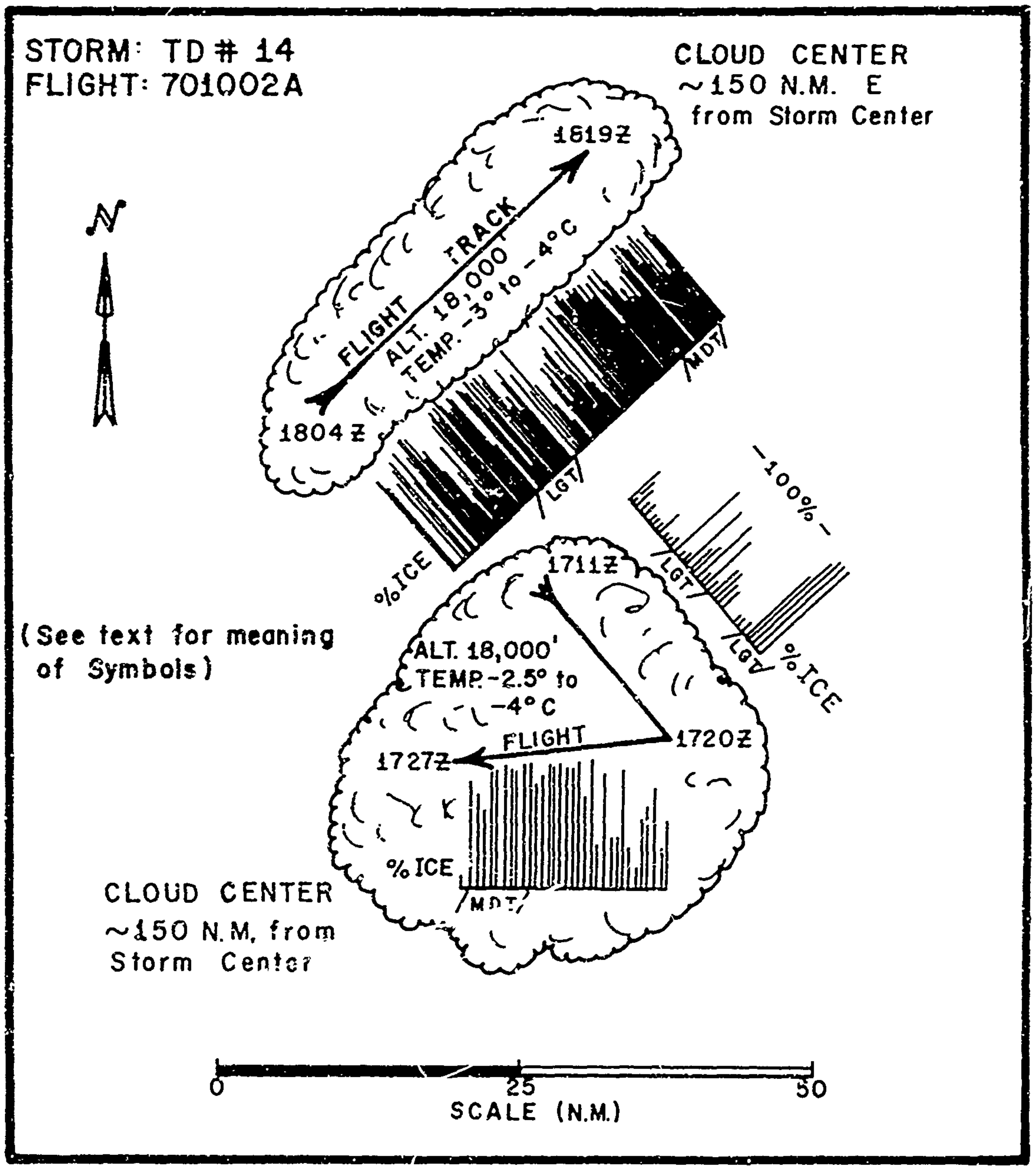


Figure G-1b. Sampling locations in Tropical Depression Number 14.

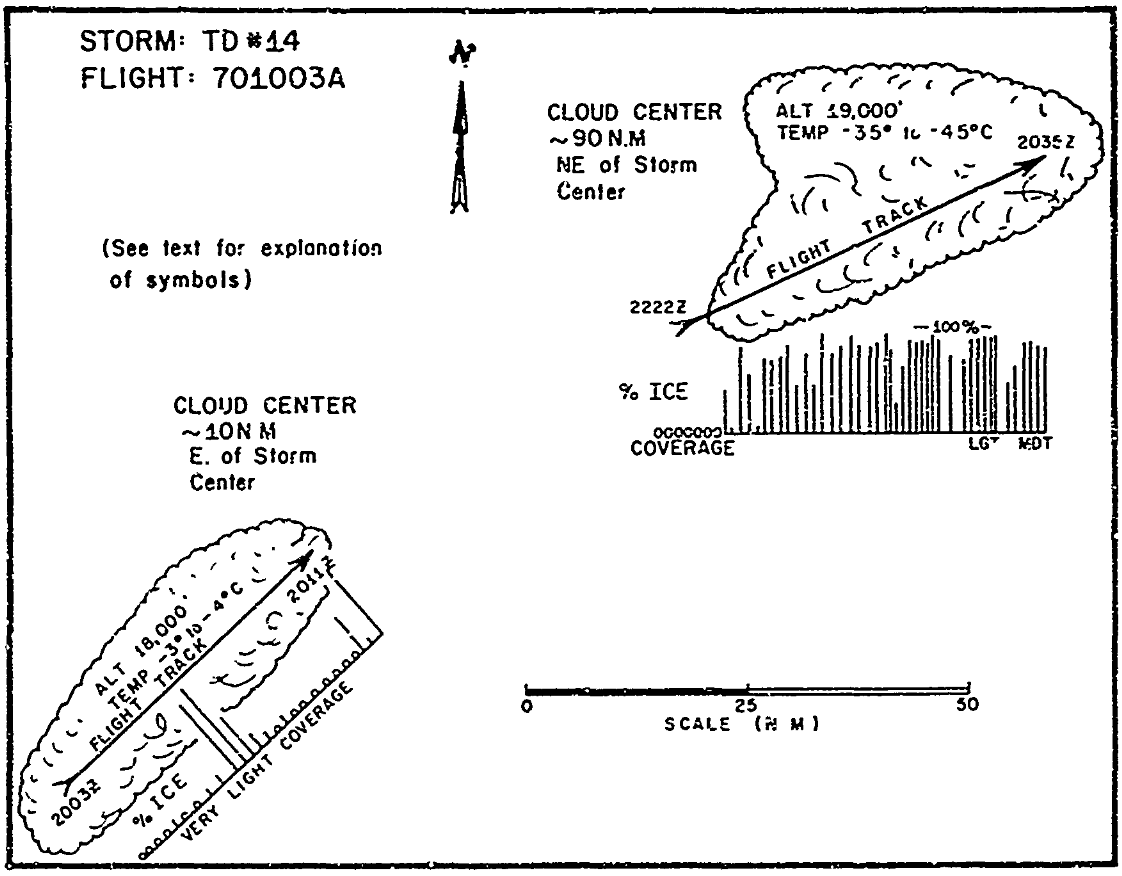


Figure G-1c. Sampling locations for Tropical Depression Number 14.

on figure G-1c the two clouds were slightly farther apart than is shown. The cloudy shapes represent the approximate extent of visible cloudiness, and the crosshatched area on figure G-1a is the area where a significant radar echo was observed. The scale is constant on all the figures; altitudes, temperatures, and the relationship of each cloud to the storm center are indicated.

A summary of all the results is shown in figure G-2. At the time the data were taken Tropical Storm Inga was increasing in intensity and had just produced hurricane-force winds. "Felice" appeared to be developing into a hurricane but it never became one. Tropical Depression No. 14 never did reach the status of a tropical storm, but the same storm system had flooded the island of Barbados and subsequently caused massive flooding in Puerto Rico.

STORM	TIME	ALTITUDE	TEMP	# OBSER
TROPICAL DEPRESS. #14	2003 - 2011 Z	18K	-3.5° to -4.5°C	52
	2003 - 2019 Z	18 K	-3.0° to -4.0°C	24
TROPICAL DEPRESS. #14	1804 - 1819 Z	18K	-3.0° to -4.0°C	148
	1711 - 1727 Z	18K	-2.5° to -4.0°C	68
	1702 - 1704 Z	18K	-3.0° to -3.5°C	8
	1632 - 1633 Z	17.6 K	-2.0° to -30°C	8
	1543 - 1544 Z	11.6K	6.0° C	6
	1427 - 1429 Z	11.6 K	7.0° C	8
	1405 - 1406 Z	11.6 K	8.0° to 7.5°C	6
700915 A "FELICE"	1743 - 1745 Z	18K	-0.3° to -1.2° C	7
690930 B "INGA"	1414 - 1418 Z	19K	1.2° to -2.0°C	271
	1354 - 1408 Z	19K	2.0° to 1.0° C	111
	1247 - 1249 Z	9K	11.5° C	12

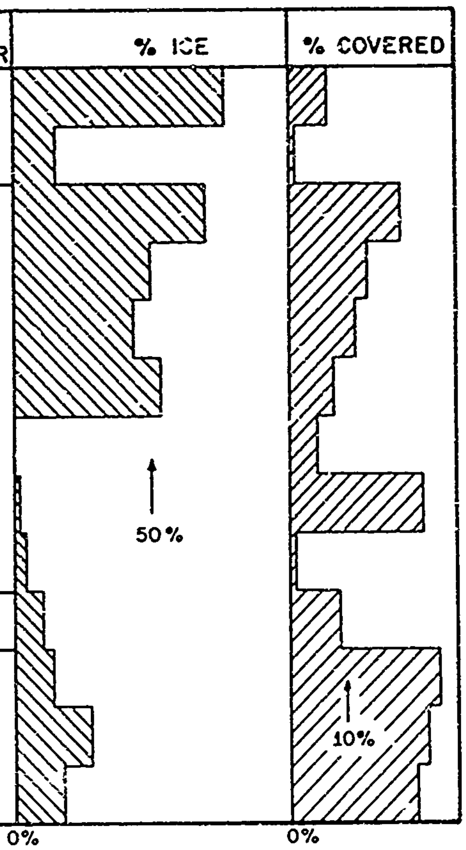


Figure G-2. Storm data.

THE ESTIMATED FRACTION ICE

The data were interpreted by viewing the projected image of the replaced crystals with a 16-mm motion picture projector. The magnification was such that 1 mm of distance on the film was projected to make 8 inches on the screen. All particles that appeared to have a crystalline character were assumed to be ice. That is, any particle with a non-spherical shape was assumed to be ice. As overall judgment was made on a single frame; one frame in approximately every 200 frames was chosen. The estimates of fraction ice are shown in detail in figures G-1a, G-1b, and G-1c. The bars represent the fraction ice which is the fraction of the total hydrometeor population that was considered ice. Below the abscissas are shown the relative quantity of hydrometeors that were sampled in terms of coverage of the 16-mm film. The blank areas indicate very light coverage. The circles represent hydrometeor samples that contained no detectable ice; the vacant spaces between the bars indicate either that no sample was taken, that there was an insufficient number of hydrometeors to estimate the fraction ice, or that the sample was too poor to make a judgment.

Several small clouds in the same general position relative to Tropical Depression No. 14 are not shown on figure G-1b. A sample taken from 1406Z to 1407Z in clear air showed the presence of cloud droplets with what appears as a small amount of ice. In this instance there were three small clouds showing radar returns within 10 n miles. An in-cloud sample taken between 1427Z and 1428Z indicated a moderate amount of liquid water and little ice. A third sample between 1632Z and 1633Z was taken outside the visible cloud and contained only ice in small quantities; again, a cloud with a radar echo was within 10 n miles. Of these samples, all were taken between the 6° and 8°C levels except the last which was taken between -2° and -3°C and, accordingly, contains mostly ice.

DISCUSSION

The observations of appreciable quantities of both liquid and solid hydrometeors outside the cloud boundaries is interesting and may shed light on the possibility of natural seeding by nearly glaciated clouds. It also points to the intangible character of a cloud boundary. At this time, however, in many of the samples, the possibility still exists

that there is an improper time correlation. An electronic counter with a digital readout is currently being added to the instrument which should help to alleviate this problem in future flights.

Figure G-3 shows a plot of the estimated fraction ice at different temperatures. The vortex temperatures may be as much as 1°C in error and most likely are a little low. The data indicate that a large portion of ice is present at the warmer temperatures (below the -5°C elevation level). Of course, the data may merely reflect the age of the storm since all the data at the colder temperatures are from Tropical Depression No. 14, and it was passing through a temporary dissipation stage at the time. It is interesting, however, that the data for Tropical Depression No. 14 are corroborated by simultaneous samples taken by the foil impactor (Meteorology Research, Inc.). The foil samples showed a large number of remarkably detailed impressions of stellar and needle crystals (see fig. G-4). These crystals did not appear in the formvar samples; but numerous, smaller, amorphous ice pieces were replicated.

The data of figure G-3 also show an anomalously high amount of ice at the warm temperatures. This may be the result of drop breakup and distortions of the drops during or before drying that created somewhat crystalline shapes. Also, ice may have been present in a partially melted state. Most likely, however, this result is purely statistical and gives a measure of the relative frequency of occurrence of inadequate particle replication and subsequent misinterpretation of the data. The worst discrepancy, a measurement of 50 percent ice at +11.5°C, corresponds to observing ice-like characteristics in only four frames in eight in a sample of poor quality. The size of the error bars indicates roughly the level of confidence that can be placed in the value. (The most significant data point is derived from judgments on 278 frames.)

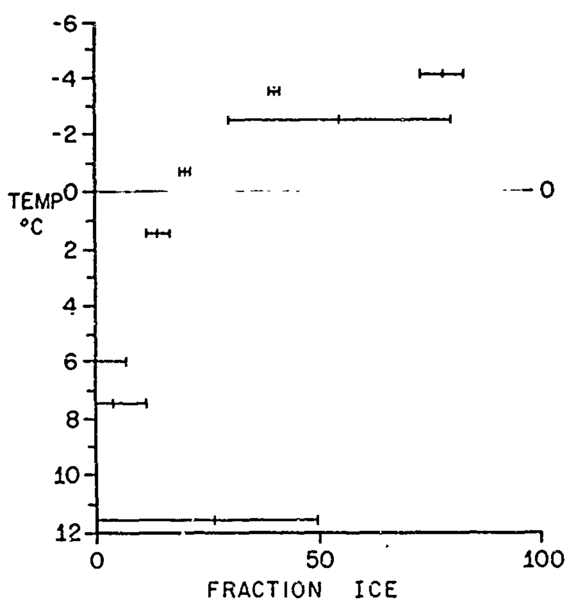


Figure G-3. Fraction ice at different temperatures in tropical storms.

All the data were processed without knowledge of the flight levels, and in Tropical Storm Inga, the analysis was

Figure G-4. Impressions of stellar and needle ice crystals on the foil impactor.

repeated by both authors independently on alternate, but staggered, frames. The results are shown in figure G-5, and the data points with the error bars represent this comparison. Another comparison was made between samples in Tropical Depression No. 14, in flights at the same temperature but at slightly different times. These data are represented by the triangles.

The airborne continuous particle replicator has been criticized on several points, including: (a) the nonstatistical size of the sample; (b) the possibility of particle breakup producing misleading numbers of ice particles; and (c) the unknown collection efficiency of the sampling boom due to pressure fluctuations and flow in and out of the boom. Niemann and Mee (1970) have completed the analysis of the 1968 cloud hydrometeor data for the Experimental Meteorology Laboratory. Occasionally they found gross discrepancies in the data, even as regards the presence or absence of ice. Figure G-5 presents an appraisal of the possible data handling problems as the usefulness of the instrument is limited by one's ability to interpret the data it presents. It appears that the criticisms above (a, b, and c) are not limiting

the value of the data, but instead, the possibility of misjudgments of the data themselves are involved. Figure G-5, all in all, says that occasionally one can expect to misinterpret the data (perhaps 10 to 20 percent of the time) but, accepting this error, the device can be used to estimate the fraction ice.

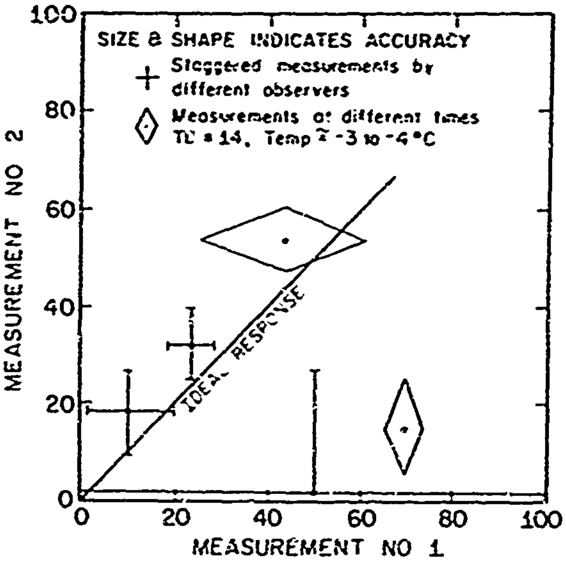


Figure G-5. The accuracy of the measurement of the fraction ice with the continuous particle replicator.

CONCLUSIONS

These data indicate that considerable amounts of ice can occur in tropical storms at temperatures above -5°C, an observation in agreement with the work of Ruskin (1967) but in contradiction to the findings of Sheets (1969) using data from Hurricane Gladys. However, the data presented here are of a limited nature and may not apply to mature storms. But, as data from more storms are analyzed and our instruments and data reduction techniques are improved, our estimates of the fraction ice in tropical storms should become more reliable.

REFERENCES

MacCready, P. B., and C. J. Todd (1964): Continuous particle sampler. *Journal of Applied Meteorology, 3,* pp. 450-460.

Niemann, B. L., and T. R. Mee (1970): Analysis of cloud particle samples for ESSA-NRL cumulus experiments. *Final Report to Experimental Meteorology Branch,* ESSA, Miami, Fla., Contract E22-96-69(N), p. 8.

Patrick, J., and A. Gagin (1971): Ice crystals in cumulus clouds--preliminary results, Studies of the microphysical aspects of cloud processes leading to the formation of precipitation. *Report No. 4, The Hebrew University of Jerusalem,* Dept. of Meteorology, Cloud and Rain Physics Laboratory.

Ruskin, R. E. (1967): Measurements of water-ice budget charges at -5°C in AgI-seeded tropical cumulus. *Journal of Applied Meteorology, 6*, pp. 72-81.

Sheets, R. C. (1969): Preliminary analysis of cloud physics data collected in Hurricane Gladys (1968). *Project STORMFURY Annual Report 1969*, U.S. Dept. of Navy and U.S. Dept. of Commerce, Appendix D.

Spyers-Duran, P. A., and R. R. Braham, Jr. (1967): An airborne continuous cloud particle replicator. *Journal of Applied Meteorology, 6*, pp. 1108-1113.

APPENDIX H

ICE-PHASE MODIFICATION POTENTIAL OF CUMULUS CLOUDS IN HURRICANES

David A. Matthews
Navy Weather Research Facility

INTRODUCTION

An examination of ice-phase modification potential of cumulus clouds in a hurricane environment is presented. The modification potential is defined as the difference between natural and modified (1) rainfall, (2) surface pressure, (3) cloud virtual temperature departure from the environment, (4) vertical velocity maximum, and (5) height of cloud tops. The modification potential is predicted by a one-dimensional steady-state cumulus model (Weinstein and Davis, 1968; Lowe et al., 1971). Modification potential results are used to test the suggestions (Gentry, 1971) that increased effects may be realized by seeding less fully developed cumulus cells that are displaced slightly outward from the present eyewall seeding area.

This paper will describe the decreases in surface pressure, the increases in rainfall, and the increases in cloud top height as derived from model simulation of ice-phase modification using 87 soundings observed within 100 n miles of hurricane eyes as well as five average hurricane soundings from Sheets (1969).

CLOUD MODEL

The Pennsylvania State University-Navy Weather Research Facility one-dimensional cumulus model (Lowe et al., 1971) was used to determine the modification potential. This model performs an integration of the vertical equation of kinetic energy for a rising cloud tower (a rising parcel in the cloud core). The basic physical assumptions of the model are as follows:

(1) None of the physical parameters investigated varies with time.

(2) The cloud tower examined has the form of an entraining jet.
(3) Entrainment is inversely proportional to the cloud tower radius.
(4) Vertical acceleration is expressed as a function of buoyancy forces and drag forces.
(5) Cloud buoyancy is generated by latent heat of condensation up to the level of nucleation. At this level, latent heat of fusion from freezing all liquid water stimulates buoyancy. Subsequent growth is solely a result of the released heat of deposition.
(6) Cloud base is located at the convective condensation level (CCL) based on surface temperature and dew point values.
(7) Seeding is simulated by freezing all liquid water at a specified temperature.

Seeding was simulated by using two nucleation temperatures, permitting an examination of the effects of different seeding materials. Temperatures of -5°C and -10°C simulated seeding by an AgI-NH_4I-acetone system and an AgI·NaI-acetone system, respectively (see app. E).

Cloud core radii were selected to correspond with those selected by Sheets (1969). Cloud bases located at the CCL were found to be in agreement with those assumed by Sheets; however, they were generally about 200 m higher (see table H-1).

Table H-1. A Comparison of Cloud Bases Selected by Sheets (1969) and Those Corresponding to the Convective Condensation Level (CCL) for the Same Five Average Soundings. Sample Size from Which the Average Soundings Were Compiled Is Also Shown.

Surface Pressure (mb)	Cloud Base Sheets	CCL (m)	Sample Size
$P \leq 995$	200	443	8
$995 \leq P \leq 999$	200, 300	415	12
$1000 \leq P \leq 1004$	300, 500	492	19
$1005 \leq P \leq 1009$	500, 750	720	26
$1010 \leq P \leq 1014$	500, 750	997	22

DISCUSSION OF MODIFICATION POTENTIAL RESULTS

Table H-2 presents average values of model results and the modification potential for five average hurricane soundings presented by Sheets (1969). The results of three cloud radii (1.5, 3.2, 5.0 km) and three nucleation temperatures (-5°, -10°, -25°C) are presented. The -5° and -10°C temperatures simulated artificial modification by AgI and AgI·NaI ice nuclei, respectively; the -25°C temperature simulated natural freezing.

Average values of cloud model results for the modified clouds in table H-2(a) show increases over values for the natural cloud. In table H-2(b) a comparison of seeding with AgI ice nuclei (-5°C) and AgI·NaI ice nuclei (-10°C) shows significant increases in the average values over those of natural nucleation. The rainfall and surface pressure values in table H-2(c) for the -5°C nucleation temperature are 8 and 63 percent higher, respectively, than those values at -10°C. This difference indicates that the AgI ice nuclei may be expected to be somewhat more effective than AgI·NaI ice nuclei in glaciating clouds. The use of a seeding material active

Table H-2. Modification Potential Results

(a) Average Values From the Natural Cloud[1] and the Modified Clouds[2]

Nucleation Temp. (°C)	-5	-10	-25	-5	-10	-25	-5	-10	-25	-5	-10	-25	-5	-10	-25
Radius (km)	Rainfall (in)			Base Press. Change (mb)			Cloud Top (m)			Virt. Temp. Depart. (°C)			Max. Vel. ($m\ sec^{-1}$)		
1.5	3.3	2.9	2.2	0.5	0.4	0.2	11094	10174	8254	1.9	1.9	1.7	4.4	9.4	9.3
3.2	5.2	5.1	4.8	1.3	1.3	1.0	13050	13174	12454	3.6	3.5	3.4	13.8	13.0	11.9
5.0	5.9	5.7	5.6	2.3	2.1	1.7	14094	13814	13854	4.2	4.4	4.2	17.4	18.2	14.9

(b) Differences in Average Values Between the Modified Clouds and the Natural Cloud

Nucleation Temp. (°C)	-5	-10	-5	-10	-5	-10	-5	-10	-5	-10
1.5	1.1	0.7	0.2	0.2	2840	2400	0.5	0.3	0.6	0.7
3.2	0.4	0.3	0.2	0.3	750	720	0.2	0.2	3.1	2.1
5.0	0.3	0.1	0.6	0.4	400	-50	0.3	0.2	3.7	3.2

(c) Average Percent Changes of Modification Potential

Nucleation Temp. (°C)	-5	-10	-5	-10	-5	-10	-5	-10	-5	-10
1.5	50%	42%	187	124%	40%	32	46%	19	7	7
3.2	9%	8%	58%	60%	10	9%	7	6	25	16
5.0	9%	4%	34%	21%	3%	-.2	10	8	25	22

[1] Nucleation temperature -25°C.

[2] Nucleation temperature -5°, -10°C.

at warmer temperatures also enables modification of smaller clouds (whose tops have reached -5°C levels but not -10°C levels) earlier in their development than does material having colder activation temperatures.

The greatest change in potential occurs in clouds of 1.5 km radius. This relationship is to some extent the property of one-dimensional steady-state models and, at best, is qualitatively valid. The explanation for the relationship is as follows:

(1) In the model the initial effect of the additional latent heat of fusion from seeding will decrease the hydrometeor concentration by evaporation. The total increase in rainfall is directly dependent upon the vertically integrated increase of hydrometeor content; hence, the net effect of seeding must produce sufficient cloud growth to increase upper level hydrometeor content to more than offset the effect of increased warming at the glaciation level.

(2) The maximum growth of unseeded small radii clouds is often limited by the higher entrainment rates which prevent growth through small, stable stratifications in the ambient atmosphere. Whereas lesser entrainment rates of unseeded larger radii clouds permit them to penetrate these small, stable layers and grow up to the tropopause. Hence, the increased buoyancy from seeding permits the smaller radii clouds to push through any stable layers, thus resulting in a large net growth and increase of total hydrometeor content.

(3) Large radii clouds, however, which in the unseeded state already have tops at the tropopause, will grow only slightly through seeding. As a result, many larger radii clouds in one-dimensional model experiments show a net decrease in total hydrometeor content (see Lowe et al., 1971). While this is a qualitatively valid relationship, strict quantitative interpretation of one-dimensional model results, in this respect, is not valid. These models do not accommodate the increased outflow at the top of these large clouds and do not permit a net increase in the total upward flux of saturated air. However, experience supports the validity of the qualitative aspects of model results.

Within the limitations of the one-dimensional model and the sounding data used, the modification potential of average cloud top heights shows increases in cloud top heights of 2800 m for 1.5 km and 750 m for 5.0 km cloud-core radii.

Examination of modification potential as a function of sounding location relative to the hurricane center was accomplished by five surface pressure categories corresponding to those of Sheets (1969) (see table H-1). Sheets derived five average hurricane soundings corresponding to these categories. Cloud model results of modification potential for these five surface pressures are presented in figures H-1(a), H-1(b), and H-2(a), and H-2(b). The 87 soundings were also divided into five groups according to the same surface pressure categories. Each sounding within a group was examined with the model, and the modification potential within each group was averaged. Figures H-1(c), H-1(d), H-2(c), and H-2(d) present the average modification potential of the five groups of soundings.

Figures H-1 and H-2 indicate that for clouds of 1.5 km radii there may be a preferred pressure location for optimum modification potential in hurricanes. In figures H-1(a) and H-1(b), this preferred location appears at a surface pressure of 1000 mb. The pattern of increasing modification potential from 1015 mb to 1005 mb is, however, probably more important than the individual maximum at 1000 mb. This pattern is consistent for all plots of modification potential in these figures both for five average soundings and for average modification potential for five groups of soundings. This pattern is also consistent for the three cloud radii examined and the two modification nucleation temperatures. This consistency of pattern adds further support to a relationship between optimum modification potential and location with respect to the hurricane center.

The pattern of high modification potential at 995-1005 mb suggests the existence of cumuli which have vertical growth arrested by small stable stratifications induced in the ambient air, but which are high enough to permit the unseeded cloud tops to reach nucleation temperature. Sounding data were not available with lower pressures to check the potential at smaller radii. The pattern of decrease of potential with further increasing pressure (to 1010 mb), however, suggests that stable stratifications and upper level dryness restrict the cloud tops to levels below the required nucleation temperature in which case the clouds would not respond to silver iodide seeding. This restriction in cloud tops is consistent with the pattern of tropical hurricane structures discussed by Palmén and Newton (1970).

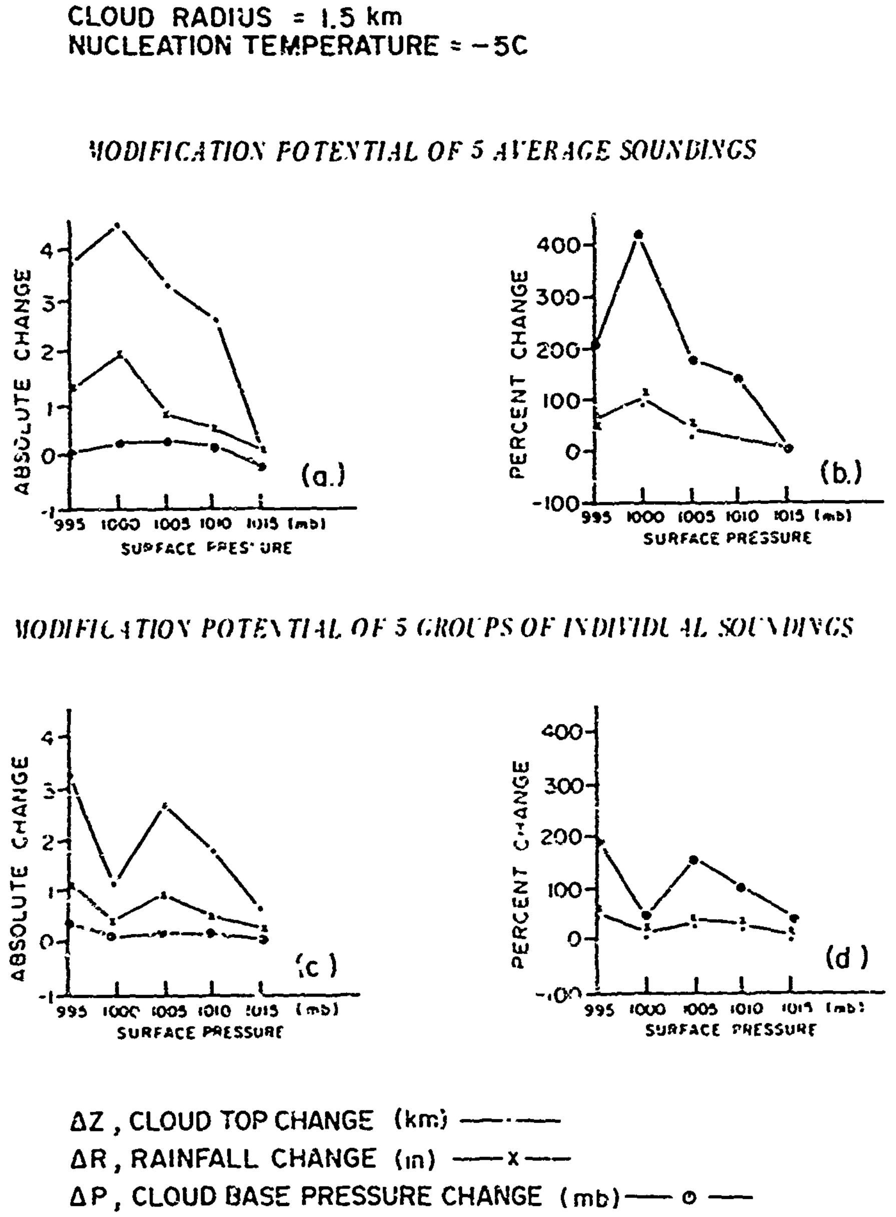


Figure H-1. Modification potential vs. surface pressure (-5°C nucleation temperature). Modification potential is divided into three categories: Cloud top change from natural cloud top, rainfall change, and surface pressure changes for clouds modified at -5°C. Both values of modification potential (a, c) and percentage changes (b, d) in modification potential are shown for five average soundings (a, b) and five groups of individual soundings (c, d).

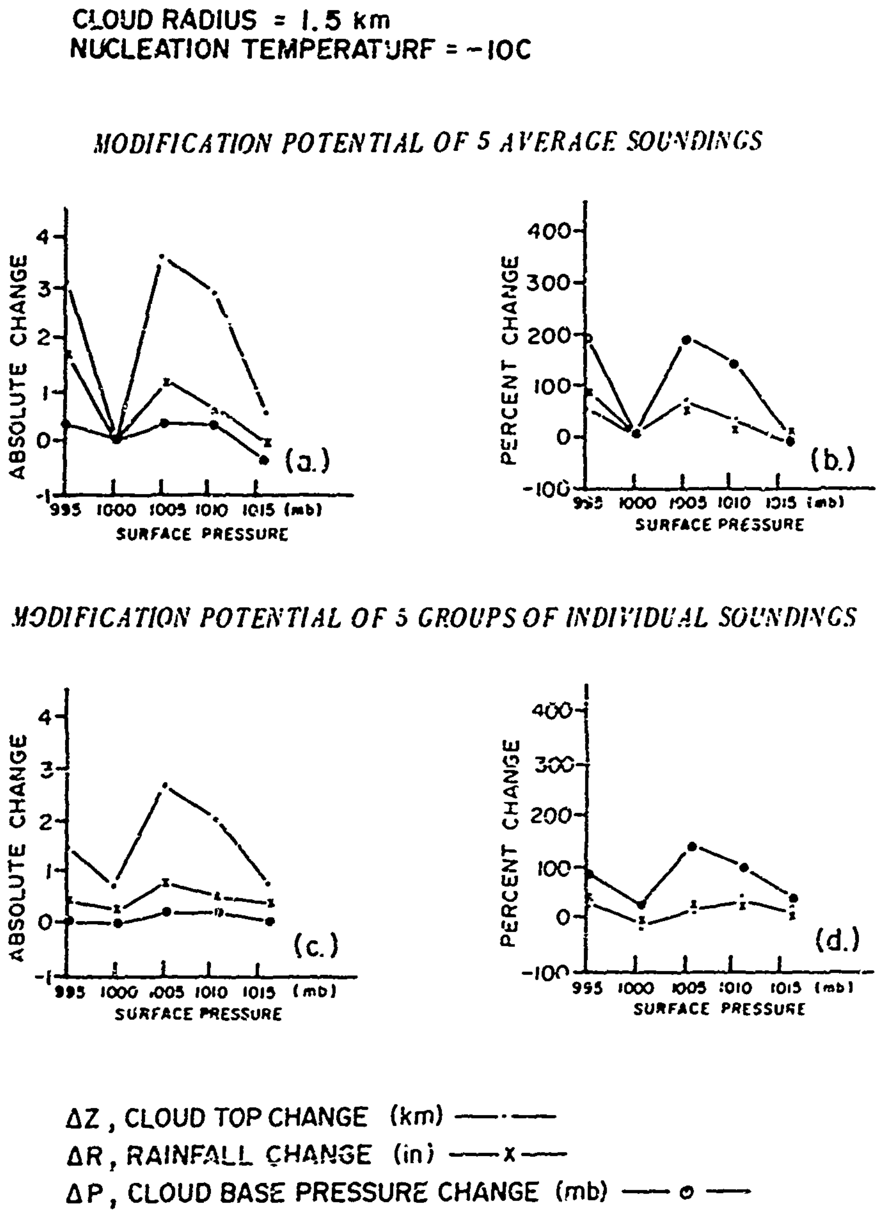


Figure H-2. Modification potential vs. surface pressure (-10°C nucleation temperature). Modification potential is divided into three categories· Cloud top change from natural cloud top, rainfall change, and surface pressure changes for clouds modified at -5°C. Both values of modification potential (a, c) and percentage changes (b, d) in modification potential are shown for five average soundings (a, b) and five groups of individual soundings (c, d).

CONCLUSIONS

Significant increases in cloud growth, precipitation, and surface pressure change indicated by a one-dimensional model appear to support the latest STORMFURY hypothesis which postulates these increases from seeding. However, the effect of these increases on the storm's maximum winds still needs to be demonstrated.

Preferred seeding distances from the eye appear to exist in the hurricane environment. These may be a function of seeding material, cloud top temperature, and cloud radii.

RECOMMENDATIONS

(1) A detailed study of modification potential of various regions of the hurricane should be made using dropsonde data and cloud models. Such a study would provide valuable information on regions of optimum modification potential. Dropsonde data should be collected from the 100- to 200-mb level down to the surface. These soundings could be made using a WC-135 flying at 40,000 ft in a large "figure-eight" pattern centered on the hurricane eye. Dropsondes made every 10 minutes during a 1-hour pattern would provide sounding data at systematic intervals from the eye in different regions of the hurricane.

(2) Improved convective models would help define optimum seeding regions and levels for hurricane abatement. Direct transmission of dropsonde data from reconnaissance aircraft to ground computer facilities would enable real-time cloud model analysis of modification potential throughout seeding operations.

(3) A study of cloud top temperatures throughout a hurricane would also provide information on which regions have optimum cloud populations for modification.

(4) The feasibility of warm cloud modification prior to cold cloud modification should be examined because warm cloud modification may permit growth of small warm clouds to temperatures at which cold cloud modification will be effective. The combined use of warm cloud and cold cloud modification techniques would permit selective seeding in all regions without cloud top temperature restrictions.

REFERENCES

Gentry, R. C. (1971): Progress on hurricane modification research-October 1969 to October 1970. Presented at *Twelfth Interagency Conference on Weather Modification*, October 28-30, Virginia Beach, Va.

Lowe, P. R., D. C. Schertz and D. A. Matthews (1971): A climatology of cumulus seeding potential for the Western United States. *WEARSCHFAC Technical Paper No. 4-71*, 78 pp.

Palmén, E., and C. Newton (1969): *Atmospheric Circulation Systems.* Academic Press, N.Y., pp. 471-522.

Sheets, R. C. (1969): Computations of the seedability of clouds in the environment of a hurricane. *Project STORMFURY Annual Report 1968*, U.S. Dept. of Navy and U.S. Dept. of Commerce, Appendix E.

Weinstein, A. I., and L. G. Davis (1968): A parameterized model of cumulus convection. *Report No. 11 to NSF*, NSFGA-777, 41 pp.

APPENDIX I

USE OF LIGHT AIRCRAFT IN STORMFURY ACTIVITIES

Dr. S. D. Elliott, Jr., and Dr. William G. Finnegan
Naval Weapons Center

INTRODUCTION

During the past three STORMFURY operating seasons, the Naval Weapons Center (NWC) has made one or two Navy-leased or contractor operated light aircraft available to the program for use during dry-run and cloudline experiment periods. This type of aircraft has provided a mainstay to other NWC programs in weather investigation and modification, and the opportunity was welcomed, both to pass on NWC experience in the effective employment of such aircraft to other STORMFURY participants, and to assess their utility in the STORMFURY operational context. As a result of three seasons' experience, some conclusions may be drawn on this topic and some recommendations offered for future STORMFURY activities.

BACKGROUND

In 1965 and 1966, NWC participation in STORMFURY included making available an A3B jet aircraft and crew to augment the RA3B's of VAP 62 in their employment as seeders. This aircraft and its military crew participated in both dry-runs, in the 1965 cumulus cloud experiments (Simpson et al., 1965) and in the aborted deployments for Betsy in 1965 (STORMFURY Annual Report 1965) and Faith in 1966 (STORMFURY Annual Report 1966). Unfortunately, the NWC A3B was lost in 1967 on a cross-country flight.

In 1967 the Naval Air Facility (NAF), China Lake, made arrangements for long-term leasing of a Cessna 210 single-engine, high-wing, four-place aircraft (fig. I-1). Equipped with retractable landing gear, full IFR instrumentation, a built-in oxygen system, and a turbo-charged engine, this 210, registry number N6877R, was capable of airspeeds in excess of 200 mph, altitudes exceeding 30,000 feet, and flight durations of 5 hours or more. Special meteorological instrumentation was installed, and external racks designed to accommodate a variety of attached and air-dropped pyrotechnic

Figure I-1. Navy-leased Cessna 210(77R). Streamlined rack for STORMFURY type air-dropped flares on port wing, boom for burn-in-place flares on starboard wing.

nucleant generators. This aircraft and similar contractor-operated aircraft provided economical and flexible tools for the development and assessment of weather modification techniques in numerous experimental projects.

The 1968 STORMFURY schedule (Project STORMFURY, Operation Plan No. 1-68) called for a dry-run exercise based at Naval Station Roosevelt Roads, Puerto Rico, with a briefing session on Monday, 5 August, and eyewall and rainband dry-runs on the 6th and 7th, the latter also to incorporate a test of the proposed cloudline experiment procedures. Cessna 210(77R) was flown to Puerto Rico for the week of 5-9 August and provided orientation and indoctrination for STORMFURY participants in current Navy-developed seeding techniques.

For 1969, the cloudline exercises were expanded to a full-scale experimental program scheduled to take place during the period 9 through 19 September (Project STORMFURY, Operation Plan No. 1-69). For this program, NWC made available two contractor-operated Cessna 401 low-wing, twin-engine, six-to-eight place aircraft (fig. I-2), having performance comparable to that of the 210 but with considerably greater

payload capacity. One 401, N3220Q, operated by Meteorological Operations, Inc., of Hollister, California, was equipped with a prototype meteorological data sensing and recording system developed by the NWC Aviation Ordnance Department, leaving only three seats available for passengers. The second 401, N32210Q, operated by Weather Service, Inc., Norman, Oklahoma, had five seats available. The twin-engine configuration of the 401 permits the use of a nose-mounted radar, and both aircraft were equipped with Bendix RDR-100 K-band weather avoidance radar systems covering a 90 degree forward sector to 80 n miles distance. Both aircraft were also equipped to carry and dispense 52 STORMFURY III air-dropped flares, externally similar to the STORMFURY I units used on Hurricane Debbie, but loaded with a shorter burning grain of EW-20 pyrotechnic mixture better suited to the cloudline operational environment (Project STORMFURY Annual Report, 1969). Other aircraft scheduled to participate in these exercises were the two NOAA DC-6's, two Navy WC-121N's, and a USAF WC-130.

All forces gathered at Naval Station Roosevelt Roads on 8 September. Cloudline experiments were conducted on 7 days during the period 9 through 18 September. The normal procedure was for the USAF WC-130 to depart Ramey AFB about 0900 local to scout the assigned operating areas for suitable cloud

Figure I-2. Cessna 401(20Q) in flight over NAVSTA Roosevelt Roads, Puerto Rico (STORMFURY Cloudline Experiments, September 1969).

groups. When these were located, within a range of 100 to 250 n miles to the northeast or southeast of Roosevelt Roads, the WC-121N's and DC-6's departed to take up their stations and establish radar surveillance and traffic control patterns (WC-121N's at 4,000 and 7,000 ft, on racetrack paths parallel to and to either side of the cloudline) and instrumented penetration and photographic tracks (DC-6's at cloud base and 18,000 ft, in a squared "figure-eight" around and through the target group). The first 401 departed the base shortly afterward, rendezvoused with the other aircraft once the latters' pre-seeding flight patterns had been established, and spent 60 to 90 minutes alternately seeding updrafts and growing cells at 18-19,000 ft (-5°C to -7°C) and withdrawing to clear the area for penetration by the upper-level DC-6. If conditions warranted, the second 401 was called out from Roosevelt Roads about 90 minutes after the first, and either continued seeding the selected group or joined the other aircraft at a newly selected target. The two 401's participated in six (20Q) and five (21Q) missions, flying a total of 30.5 hours, normally carrying three Project officials and observers each. Approximately 125 STORMFURY III flares were fired into cloudline targets. In addition to seeding and indoctrination in seeding procedures, the 401's provided photographic and visual coverage of the experiment and aided in target selection. Only limited use of the instrument package installed aboard 20Q was made, but the potentialities of the system and procedures for its maintenance and use under field conditions were established. Otherwise, aircraft performance was excellent, only one mission being aborted due to a pyrotechnic rack wiring problem aboard 20Q; 21Q was, however, able to take over and complete the mission. In addition, both 401's were used on a stand-down day for a 1.5-hour air-to-air photography mission, yielding valuable motion picture footage which has since been incorporated in NWC documentary films. The aircraft were also used for several logistic flights to transport personnel and equipment between Roosevelt Roads and San Juan.

Operationally, the cloudline experiments were regarded as entirely successful in achieving their primary purpose of establishing the flight patterns, and communications and control procedures to be used in future STORMFURY operations. Additionally, valuable meteorological data were secured on the behavior of natural and artificially modified linear cloud arrays similar to hurricane rainbands. Finally, most of the key personnel in the STORMFURY program were directly exposed to Navy developed procedures for selecting and seeding individual clouds, which would not have been possible with the high-performance A6 jet seeder aircraft. The success of the cloudline experiments was thus due in no small measure to the availability and capabilities of 20Q and 21Q (Project STORMFURY Annual Report, 1969).

1970 DRY-RUN/CLOUDLINE OPERATIONS

For 1970, the STORMFURY Cloudline exercises were scheduled for the period 24-31 July, immediately following the dry-run exercises 20-23 July at Naval Station Roosevelt Roads (Project STORMFURY Operation Order No. 1-70). During the previous year, one of the NOAA DC-6's (39C) as well as the B-57 had been equipped to dispense STORMFURY pyrotechnic flares of the WMU-2 type, while the DC-6 additionally carried an RFF-developed acetone-burning nucleant generator. It was therefore decided that only one Cessna 401 (21Q) would be brought by the NWC staff, equipped for air-dropped flares but without a data-collecting system in order to retain maximum seating space. The Cessna arrived in Puerto Rico on the evening of Wednesday, 23 July. On the 24th and 25th it flew four training missions, during which various military and civilian personnel involved in ordnance development, seeding, and operational activities connected with STORMFURY received intensive indoctrination in seeding procedures. On the 26th, a project stand-down day, members of the NWC staff flew an experimental mission to test two newly developed types of air-dropped flares under consideration for future STORMFURY applications. On the 27th, 28th, and 29th, 21Q participated in cloudline experiments together with the two DC-6's, the B-57, two WC-121N's, and the WC-130. On the evening of the 29th, the Cessna departed for China Lake, to meet other commitments. In summary, 21Q made a total of eight training and experimental flights, for a total duration of 17.7 hours, during which approximately 80 rounds of various types of pyrotechnic flares were fired. In addition, several photographic and logistic flights were conducted. These light aircraft thus once again provided a significant contribution to STORMFURY training and experimental activities.

CONCLUSIONS

Experience with the use of light aircraft in connection with STORMFURY activities, as cited above, leads to certain conclusions regarding their utility in the following fields:

(a) *Training*. NWC-sponsored light aircraft provided training in seeding techniques pertinent to the hurricane environment for key STORMFURY personnel during one flight in 1968 and four in 1970, in connection with the dry-run exercises. The cloudline experiments in 1969 and 1970 provided further opportunities for such indoctrination. This was accomplished at much lower cost ($50 per flight hour for the single-engined 210, and $100 per hour for the 401 twin), and

with much greater flexibility than would have been the case had the larger aircraft employed in STORMFURY hurricane operations been used for this task. This use should definitely be continued during future STORMFURY seasons.

(b) *Independent Experiments.* As exemplified by the pyrotechnic tests conducted on 26 July 1970 and by some of the tests carried out during the 1969 and 1970 cloudline exercises, these light aircraft are ideal for preliminary testing of novel seeding materials and techniques, operating either alone, or in conjunction with at most, two other aircraft. It is essential that such tests be planned to permit maximum flexibility in operations, since the results obtained have only limited predictability. Such tests will undoubtedly be carried out in future seasons, as new nucleant-generating systems are developed.

(c) *Organized Experiments.* The utility of the light aircraft in complex, preplanned operations involving several other airplanes is more limited, although still substantial. Although the Cessna 210 and 401 aircraft have performance capabilities not significantly inferior to the DC-6's and WC-121N's and superior in the case of altitude, their limited flight duration (4½ to 5 hours for over-water operations with a full passenger load, and 2 to 3 hours of oxygen for high altitude flight) requires their use in relays (as in 1969, and with the B-57 in 1970) for protracted experiments. Similarly, their maximum effective operating radius at sea of approximately 250 miles, when coupled with the requirement that experimental activities be conducted at least 100 n miles at sea (to avoid complications inherent in the use of controlled airspace) limits their usefulness when suitable clouds are scarce. It should be noted, however, that high-performance aircraft such as the A6 and B-57 are similarly limited in flight duration, although not in range. Available navigation and radio equipment (VHF only) are also unsuited for long range use at sea. Within these limitations, however, continued use of light aircraft in cloudline experiments appears desirable.

(d) *Hurricane Operations.* It is doubtful whether light aircraft of this class would be of any utility in an actual hurricane seeding operation, except possibly in a situation in which outlying rainbands pass relatively close to a suitable operating base.

(e) *Miscellaneous.* On many occasions during the last 3 years, the NWC-provided aircraft provided an inexpensive, rapid, and flexible means for transporting personnel and equipment. They also proved highly effective in obtaining photography for both documentation and data assessment purposes.

It thus appears that continued use of at least one light aircraft (preferably twin-engined for safety and performance reasons) is desirable for future STORMFURY seasons, at least in connection with dry-run, cloudline and equivalent activities. The Naval Weapons Center, plans to continue providing this capability.

REFERENCES

Simpson, J., et al. (1965): *STORMFURY Cumulus Seeding Experiment, 1965*, Preliminary Summary, Project STORMFURY Report No. 1-65. U.S. Navy/Weather Bureau, 1 November.

STORMFURY Staff (1966): *Project STORMFURY Annual Report, 1965*. U.S. Dept. of Navy and U.S. Dept. of Commerce.

STORMFURY Staff (1967): *Project STORMFURY Annual Report, 1966*. U.S. Dept. of Navy and U.S. Dept. of Commerce.

STORMFURY Staff (1968): *Project STORMFURY Operation Plan No. 1-68*. U.S. Fleet Weather Facility, Jacksonville, Florida. p. D-1.

STORMFURY Staff (1969): *Project STORMFURY Operation Plan No. 1-69*. U.S. Fleet Weather Facility, Jacksonville, Florida. p. G-1.

STORMFURY Staff (1970): *Project STORMFURY Annual Report, 1969*. U.S. Dept. of Navy and U.S. Dept. of Commerce.

STORMFURY Staff (1970): *Project STORMFURY Operation Order No. 1-70*. U.S. Fleet Weather Facility, Jacksonville, Florida. pp. D-I-1, D-V-1.

APPENDIX J

USE OF ECHO VELOCITIES TO EVALUATE HURRICANE MODIFICATION EXPERIMENTS

Peter G. Black
National Hurricane Research Laboratory

ABSTRACT

Echo velocities computed from airborne radar at six time intervals over the entire storm before and during the seeding of Hurricane Debbie on 20 August 1969, reveal that mean echo speeds equaled or exceeded cyclostrophic winds computed from 12,000-ft. D-value data as well as measured 12,000-ft winds after a correction for water motion was applied. In the time period from just before seeding began to just after seeding ended, azimuthal mean echo speed increases ranging from 30 knots at the 100 n mile radius to 10 knots in the outer eyewall were found. In this same period, the mean echo crossing angle changed from 5 degrees inward to 5 degrees outward at the 100 n mile radius. Deviations about the azimuthal mean echo speed and crossing angle indicated that wave number 2 accounted for nearly all of the variance around the storm's circumference at all radii. The deviations remained fixed in time between radii of 25 and 150 n mile, but rotated with the major axis in the inner and outer eyewalls. It is suggested that these echo motions approximate the air flow in the lower levels of the hurricane.

INTRODUCTION

For some time attention has been focused on the symmetrical features of the hurricane circulation, with the only asymmetry on the scale larger than that of the rainbands being introduced by the motion of the storm. Aircraft and ship data collected in storms have been too sparse in space and time to

adequately describe other asymmetries of these larger scales. Considerable time variation in wind speed profiles on the rainband scale and smaller through several hurricanes has been measured. This has been attributed to the "natural variation" in storm intensity. However, it is a distinct possibility that the time change in these wind speed profiles can be partly due to the advection of horizontal asymmetries. Furthermore, in hurricane modification experiments, the possibility exists that the seeding location relative to horizontal asymmetries may have an important bearing on the outcome of the experiment.

Therefore, in this report, an attempt has been made to define the low-level asymmetries in a hurricane and their change with time using the motion of small precipitation echoes. Ten-minute time periods were used to define a motion field over a portion of the hurricane circulation within 150 n miles of the storm center. Several of these time periods were composited to give an average 1-hour motion field over the entire hurricane circulation. Radial and azimuthal profiles of the echo speed and crossing angle were constructed for 6 one-hour time periods. These profiles were compared with aircraft wind measurements where they were available.

Many authors have computed echo velocities in hurricanes and attempted to relate these velocities to winds at a particular level. Ligda (1955) used land based radar in Florida to compute echo velocities in the hurricane of 23-28 August 1949. He coined the term "spawinds" to refer to the motion of isolated convective cells since he said they correlated well with the 700 mb winds. Senn et al. (1960a,1960b) and Senn (1963, 1965) have done extensive work on the calculation of echo velocities within Hurricanes Edna of 1954; Connie, Diane, and Ione of 1955; Audrey of 1957; Daisy and Helene of 1958; Debra of 1959; and principally, Donna of 1960. He found systematic variations in echo velocity with azimuth around the storm, with day vs. night, with land vs. sea, with storm speed, and with echo crossing angle. Senn compared echo velocities with aircraft winds and found that in general the echoes moved slower than the winds at all levels. Watanabe (1963) computed echo velocities in Typhoon Nancy of 1961 from a ground based radar on Okinawa. He found very good agreement between the echo velocities near rawinsonde stations and the mean wind between cloud base and cloud top.

Fujita (1959) used airborne radar to compute echo velocities in Hurricane Carrie of 1957. His technique involved placing each radar photograph at the aircraft position given by the Doppler navigation system and then tracing the successive position of various radar echoes. However, any error in

the Doppler fix will result in an error in the echo velocity. Jordan (1960) also used airborne radar to compute echo velocities in Hurricane Daisy of 1958. He used the hurricane center as a reference point for his calculations. He noted relatively good agreement between his echo velocities within the eyewall region and aircraft measured winds at 13,000 ft.

The above authors have shown that no unique relationship appears to exist between echo velocities and winds at a particular level. This may appear to be a severe limitation in using echo velocities to evaluate hurricane seeding experiments. However, the data presented in the next section will show that this shortcoming is not so bad as it may seem, especially when the proposed mechanism governing echo motion, presented in a later section, is taken into consideration.

DATA ANALYSIS

In this study, airborne radar data collected during the seeding experiment in Hurricane Debbie, 20 August 1969, were used. Echo velocities over a 10-minute period were computed from primarily the Air Force APS-64, 3-cm radar on board a WB-47 flying at 39,000 ft. Echo velocities were also computed from the Navy APS-20, 10-cm radar on board a WC-121N flying at 1,000 ft. See Black et al. (1971) for the specifications of these radars. Fujita's movie-loop technique was used to construct picture sequences using airborne radar photographs taken at 30-sec intervals which had been registered with respect to the hurricane center and true north. This technique yields extremely accurate results since 30 sec continuity on the echo motion can be obtained, and any errors in positioning the photographs with respect to the same fixed point and orientation (namely the hurricane center and true north, respectively) will be immediately obvious by a jump in the echo position when projected in movie form on a screen.

Short period oscillations in the storm speed during the 10-minute interval used for computing echo velocities are not thought to be large enough to bias the echo velocities by more than 1 or 2 knots. Senn (1965) has indicated average fluctuations in the speed of Hurricane Donna on the order of about 5 knots in 1 hour with maximum fluctuations on the order of 10 knots in 1 hour. Such fluctuations were not detected in the motion of Hurricane Debbie. However, errors in aircraft navigation and eye location were such that they could have existed.

Usually, four or five 10-minute average echo velocity fields were composited to obtain the echo velocity field characteristic of a 1-hour time interval. The short period storm motion fluctuations should be sufficiently random to cancel out when the 1-hour composites are compared with each other.

ECHO VELOCITY PROFILES

One-hour echo velocity composites were prepared for the time periods 1100-1200Z, 1600-1700Z, 1700-1800Z, 1800-1900Z, 1900-2000Z, and 2000-2100Z. Usable data were not available for any other time periods. The above times cover a period from 1 hour before seeding began (about 1200A) to 1 hour after seeding ended (about 2000Z).

The storm was divided into four quadrants defined by perpendicular lines oriented 45 degrees to the left and right of the storm motion vector (310 degrees in this case). All the echo velocity vectors within each quadrant were then composited into radial profiles of speed and crossing angle (defined as positive inward). The resulting scatter diagrams for selected time periods are shown in figures J-1 to J-3. The mean scatter was about 10 knots for the speed and about 10 degrees for the crossing angle, which is well within the scatter that would be introduced by short period fluctuations in the storm speed. A portion of this scatter (perhaps half) can be accounted for by azimuthal variations in echo velocity as will be seen in a later section.

Relative wind profiles measured by RFF aircraft at 12,000 ft as well as computed cyclostrophic wind profiles were superimposed, where available, in the left and right quadrants. The cyclostrophic winds were computed from

$$C = \sqrt{rg \frac{\Delta D}{\Delta r}} \qquad (J.1)$$

where r is the radius from the storm center, Δr was chosen as 2 n miles, and ΔD was the D-value gradient which was subjectively smoothed. Relative winds based on reports from Navy aircraft at 1,000 ft, 6,000 ft, and 10,000 ft are also plotted where available.

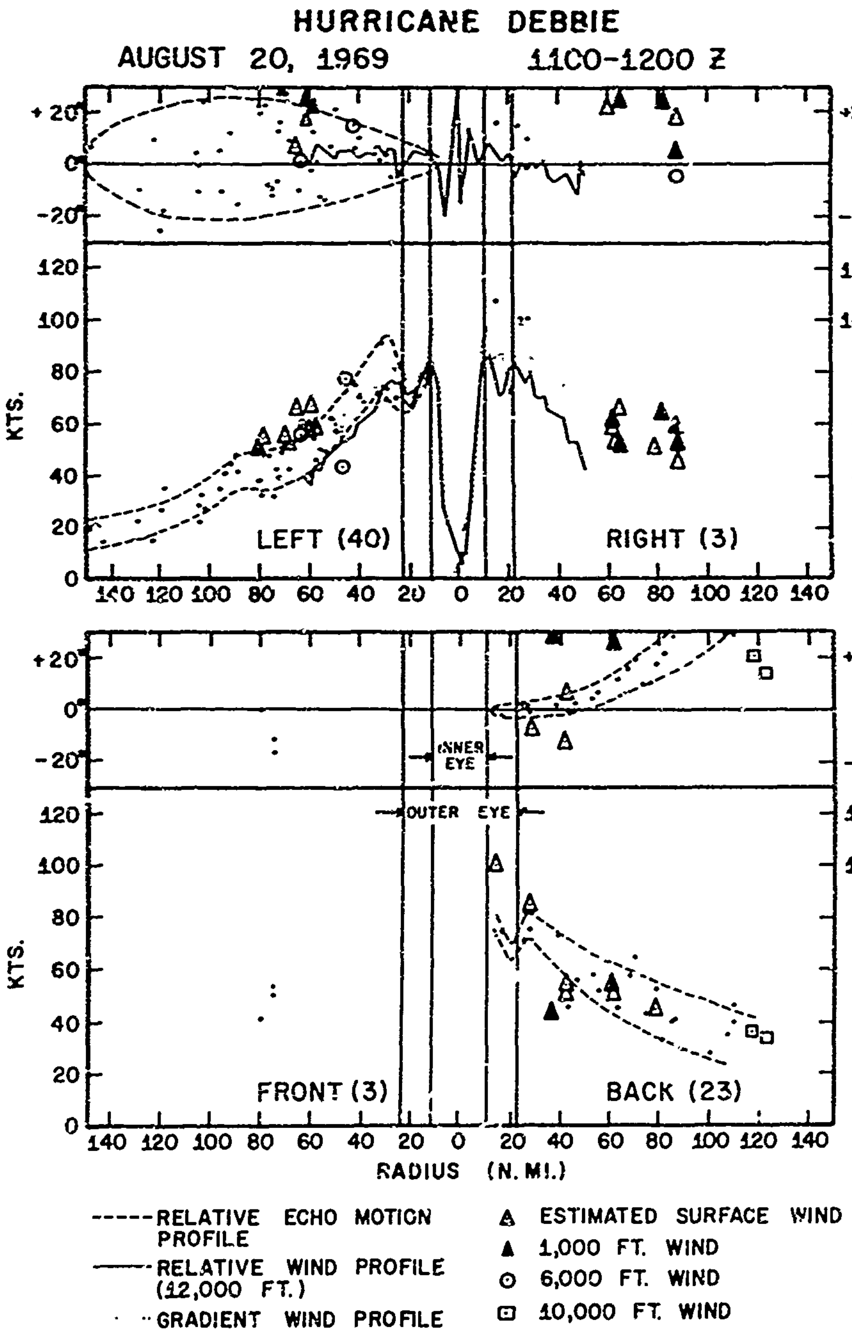


Figure J-1. Relative echo speed (bottom panel) and crossing angle (top panel) profiles compared with relative 12,000-ft wind and cyclostrophic wind profiles, as well as scattered surface, 1,000 ft, 6,000 ft, and 10,000 ft relative wind reports for 1100 to 1200Z, 20 August 1969. The vertical lines indicate the inner edges of the inner and outer eye-walls.

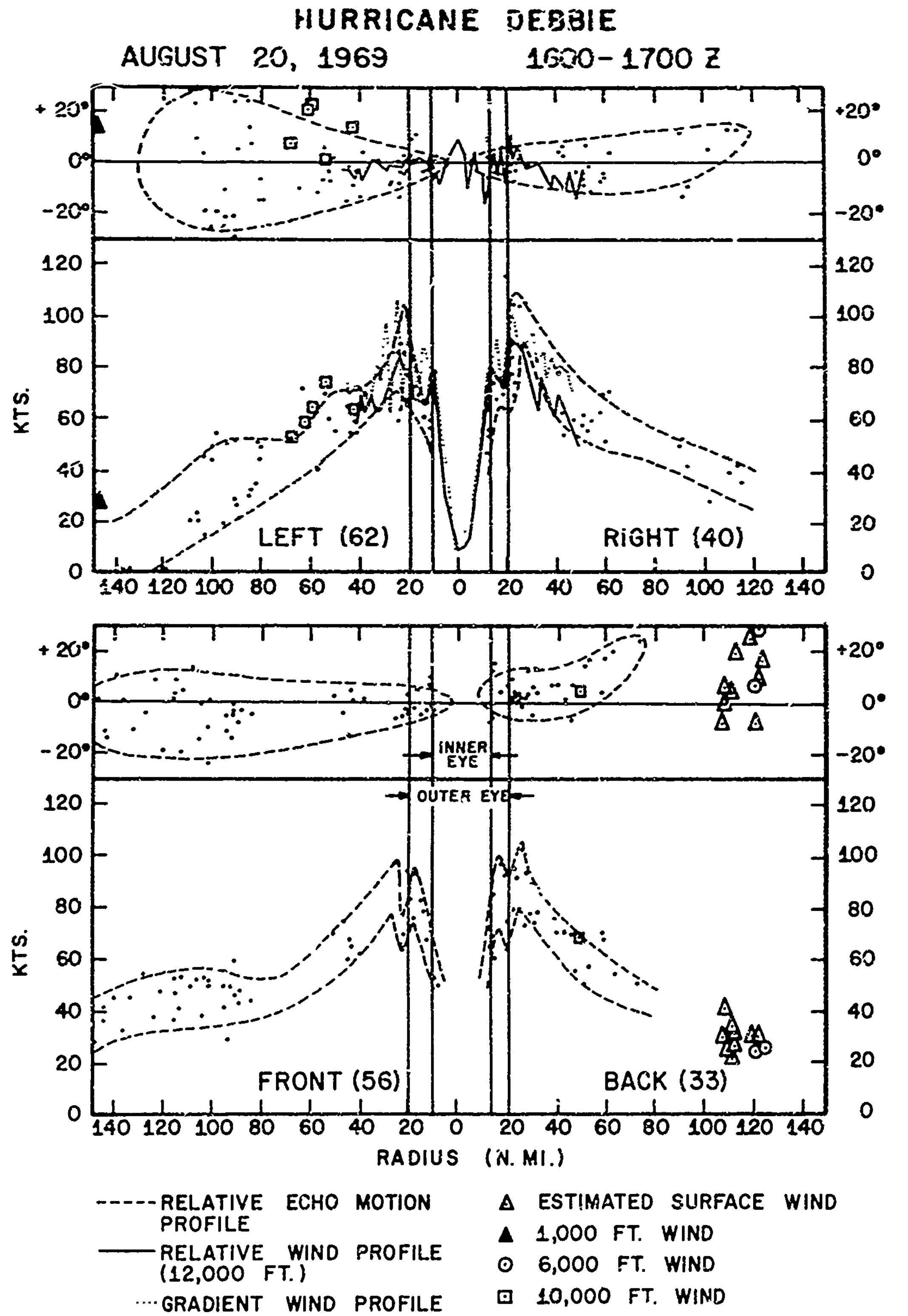


Figure J-2. Same as figure 1 except for the time period from 1600 to 1700Z, 20 August 1969.

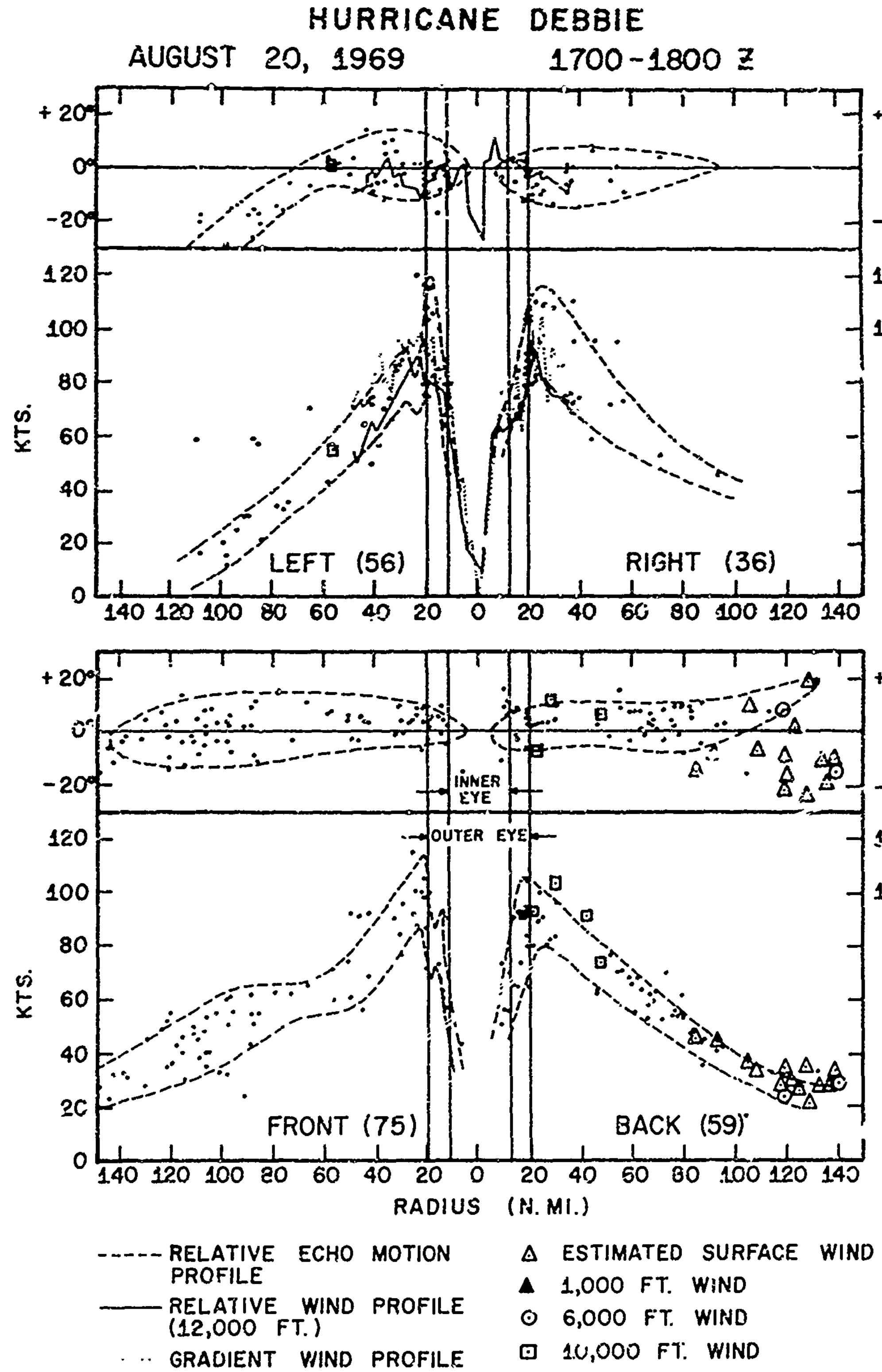


Figure J-3. Same as figure 1 except for the time period from 1700 to 1800Z, 20 August 1969.

The mean location of the inner edge of the inner and outer eyewalls during the hour is indicated by the vertical lines. Seeding times, radii, and azimuths are given in table J-1.

The results indicate that the mean relative echo speeds are generally in balance with the cyclostrophic winds at 12,000 ft. However, in some cases, the relative echo speeds exceed the cyclostrophic winds by about 5 knots (e.g., left quadrant, 30-40 n miles radius, fig. J-1; and right quadrant, 30-50 n miles radius, fig. J-3). The measured relative winds at 12,000 ft appeared to be about 10 knots less than the mean relative echo speeds and the cyclostrophic winds out to a radius of 40 n miles. Where data are available beyond that radius, there appears to be much closer agreement between the profiles.

The discrepancy between the relative winds and the cyclostrophic winds might possibly be explained by the effects of the moving sea surface on the airborne Doppler radar used to measure the aircraft ground speed from which the winds are calculated. Figure J-4 represents an extension of Grocott's (1963) work by Black et al. (1967) in relating sea surface movement to wind speed. Using data from Hurricane Flora of 1963, the data of Grocott were extended to hurricane force winds. Figure J-4 indicates that for wind speeds ranging from 75 knots to 100 knots (corresponding to those measured within 40 n miles of Hurricane Debbie) a water motion of from 5 to 10 knots or more would be possible. The water motion has been shown to be nearly parallel to the wind out to at least twice the radius of maximum wind (22 n miles in the case of Debbie). The Doppler winds would thus be an underestimate of the true wind by 5 to 10 knots or more within 40 n miles of the storm center. When this correction is applied, the relative measured winds become equal to and in come cases slightly greater than the cyclostrophic winds.

Table J-1. Seeding Times and Locations for Hurricane Debbie, 20 August 1969.

Seeding Time (Z)	Range Interval (n miles)	Azimuth (from true North)
115630-115830	15-22	022-001
140140-140330	12-25	044-034
161345-161545	11-25	357-351
175750-175950	12-27	018-010
195350-195620	18-34	356-359

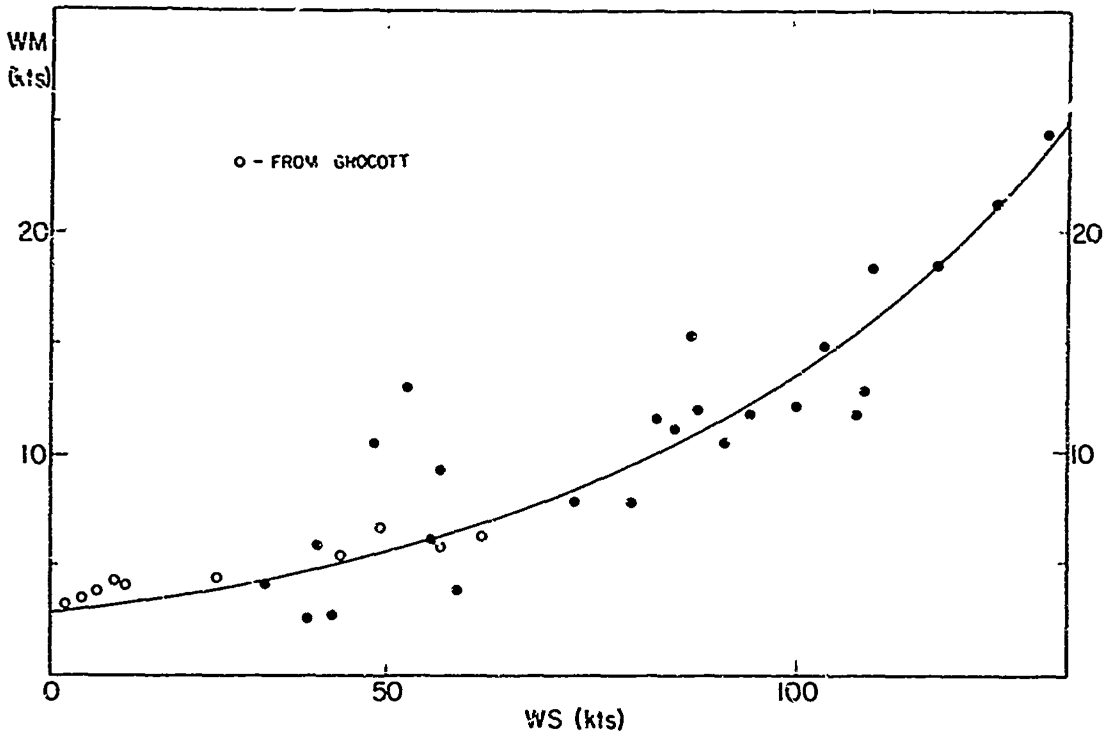


Figure J-4. Sea surface water motion (WM) as a function of wind speed (WS) (after Black, 1967; Grocott, 1963).

There are several possible theoretical explanations for the suggested inbalance between cyclostrophic and measured relative winds. Among these are (1) storm not in steady state (especially true if storm is responding to seeding), (2) frictional accelerations, and (3) vertical and horizontal advection of momentum by the asymmetries.

Relative winds measured at 1,000 ft and surface winds estimated from the appearance of the state of the sea were made generally between radii of 50 and 125 n miles and tended to agree remarkably well. They were in general about 10 knots greater than the mean relative echo speed profiles in the left and back quadrants, but about 15 knots less than the echo speed profiles in the right and front quadrants. Ross (1971), in a recent study, has been able to relate areal coverage of white caps on the sea surface to wind speed at the 20-m level, up to a wind speed of 50 knots. He has found that the 20-m wind is about 20 percent less than the wind at a flight altitude of about 1,000 ft. Therefore, it is felt that the estimated surface winds are too high and should be reduced by at least 10 to 15 knots. The 6,000 ft and 10,000 ft winds were in relatively good agreement with the echo speed profiles.

A time history of the mean relative echo speed and crossing angle profiles is given in figure J-5. The figure indicates that the echo speeds tend to increase with time at radii of from 40 to 150 n miles in all quadrants of the storm. The increase was on the order of 10 to 20 knots. This result is consistent with the results of Hawkins (1971) which indicated an increase in the winds in the left quadrant at radii from 75 to 200 n miles of 10 to 15 knots from well before to well after the seeding experiment. This result is further substantiated by the time change of the azimuthal mean echo speed given in a later section.

It should be noted that the echo speeds fall off most rapidly in the left quadrant, reaching a mean value of about 10 knots at 150 n miles radius. A sharp shear line has been shown to exist in this quadrant at radii larger than 150 n miles by the low-level streamline analysis of Fujita and Black (1970), based on low cloud motions. The echo speeds fall off to about 30 knots at 150 n miles radius in the right and back quadrants. This result is also illustrated clearly in the azimuthal profiles.

Figure J-5 also shows that the crossing angle becomes more negative with time in all quadrants, indicating the echoes are tending to move outward more as time progresses. Of special note is the change evident in the back quadrant where crossing angle changes from 20 degrees inward at 75 n miles radius before seeding to 15 degrees outward after seeding are evident.

These results tend to be in the sense anticipated by the numerical modification experiments of Rosenthal (1971) which predicted an increase in the winds outside the seeded eyewall region, even as the maximum wind was reduced and moved outward. Therefore, these results appear to support the contention that a modification of Hurricane Debbie was indeed achieved.

A POSSIBLE MECHANISM GOVERNING ECHO MOTIONS IN A HURRICANE

Some clarification is needed concerning the mechanism responsible for the observed echo velocities. It was mentioned earlier that in some cases, agreement was found between echo speeds and the 700 mb winds. This is probably fortuitous. Watanabe (1963) has suggested, using rawinsonde data, that echo velocities agree best with the mean wind between the echo base and the echo top, which Senn (see app. K) has shown is generally not much higher than 30,000 ft. This

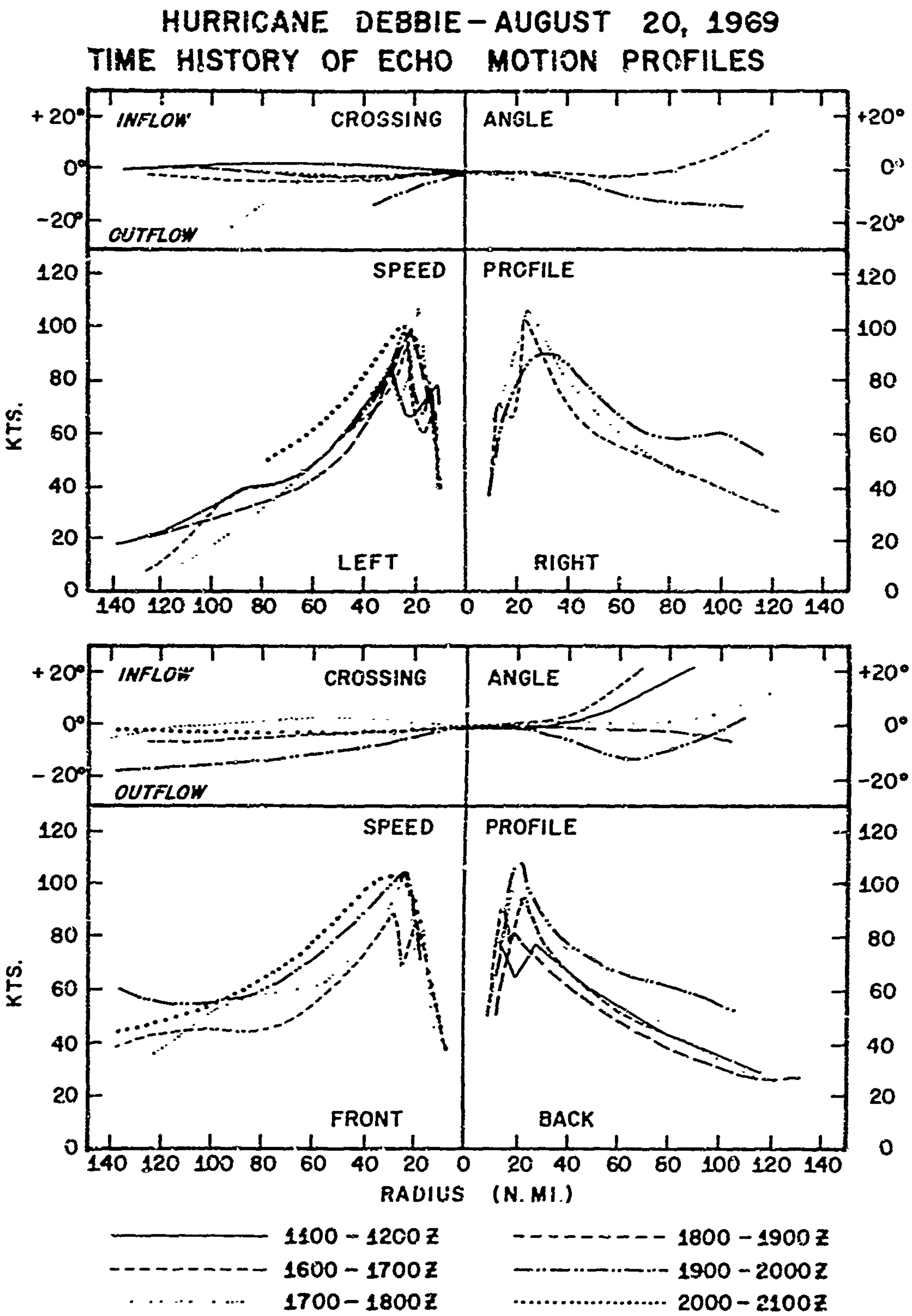


Figure J-5. Time change of echo speed and crossing angle profiles for four quadrants of Hurricane Debbie.

mean wind, in many cases, appears to be nearly that at 10,000 ft (about 700 mb). However, Senn (1965) has observed that in general, echoes move fast early in their lifetime and slower later in their lifetime. Watanabe, in order to account for the scatter in his data about the 700 mb wind, suggests he was observing echo velocities at different stages in their lifetime, and hence moving at different velocities.

It is now suggested that the reason for the above reported behavior could be that the growing echo, sustained by a substantial vertical velocity (probably greater than 10 m sec^{-1}), moves with the horizontal momentum of the inflowing air near cloudbase. Even though the vertical profile of the echo may be tilted, due to vertical wind shear, the echo boundary, as outlined by Gentry et al. (1970), will still move with the low-level wind speed as long as the vertical velocity is sustained. In fact Senn (1966) and Black et al. (1971) have used the vertical tilt of radar echoes to infer the shear, assuming precipitation particles were falling at their terminal velocities. Therefore, at all levels in which the radar is observing actively growing convective echoes, the echo boundary of an actively growing echo will move with the low-level speed. The present data indicate this since most of it was taken from an aircraft at 39,000 ft, and the resultant echo velocities agreed best with the low-level winds. The echo motion data of Jordan (1960), which were representative of the level from 20,000 to 30,000 ft, also tended to agree better with the lower-level winds.

In the case of precipitation falling through weak diluted updrafts (on the order of 1 or 2 m sec^{-1}), the tilt of the echo would still be in the same sense as outlined in the above paragraph, but more tilted. In this case, the echo boundary could be expected to move with nearly the speed of the wind at the precipitation generating level. However, this type of echo tends to be more diffuse than the actively growing one and hence harder to follow. Therefore, most of the echoes used in this study were most probably near their mature stage.

If the above argument is valid, most of the echoes probably represent the flow in the inflow layer, modified slightly by entrainment. Trends in the mean echo velocities in particular quadrants or range intervals should therefore indicate trends in the low-level flow field. Deviations from the mean echo velocities around the circumference of the storm at different radii are then a measure of the asymmetries in the low-level flow.

THE LOW-LEVEL ASYMMETRIC STRUCTURE OF HURRICANE DEBBIE AS REVEALED BY ECHO VELOCITIES

Study of the variation in echo velocity with azimuth in Hurricane Debbie is presently underway. Preliminary results indicate the following:

(1) The mean echo speeds around the circumference of the storm at range intervals of 18-28 n miles (outer eyewall), 28-50 n miles, 50-75 n miles, and 75-150 n miles increased with time as shown in figure J-6. Increases from ½ hour before seeding began until ½ hour after seeding ended ranged from 30 knots at the outermost range interval to 10 knots in the outer eyewall. The echo speeds decreased in this time period in the range interval from 10-15 n miles (inner eyewall) by about 20 knots.

(2) Superimposed on the upward trend beyond the inner eyewall was a shorter period fluctuation, indicated by the thin solid lines on figure J-6. At each range interval, a 5-10 knot increase appeared to follow each seeding followed by a slightly smaller decrease until the next seeding, when another increase occurred. Therefore, there appear to be three time scales of echo motion: (a) the long period trend over several hours, (b) the shorter period fluctuations with a period of an hour or two, and (c) the deviations about the mean with a period of less than 1 hour.

(3) The echo speed deviations from the mean averaged about 11 knots. At the two outer range intervals, the deviations increased with time. At the three inner range intervals, the deviations decreased with time.

(4) The mean crossing angle around the circumference of the storm decreased at all range intervals, indicating less inflow in the time period studied. This is shown in figure J-7. The largest decrease occurred in the outer range interval where a change of from about 5 degrees inward to about 5 degrees outward was measured. At the other range intervals the decrease was about 5 degrees inward to about zero. The average maximum deviations from the mean generally tended to decrease during the time period studied. The average maximum deviation during the time period was about 8 degrees, the largest deviations occurring at the outermost range interval.

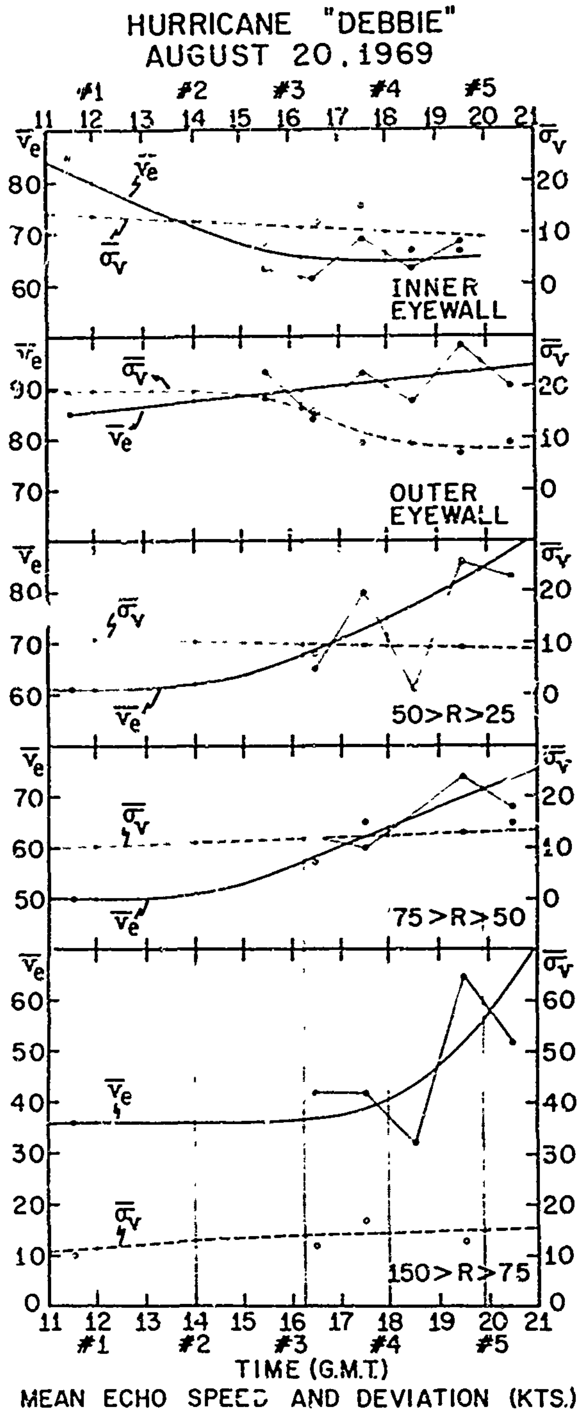


Figure J-6. Azimuthally averaged echo speeds at selected range intervals together with the mean maximum deviations about the azimuthal mean. Scale for the mean values (solid circles) is on the left and the scale for the deviations (open circles) is on the right. The thin vertical lines indicate the seeding times.

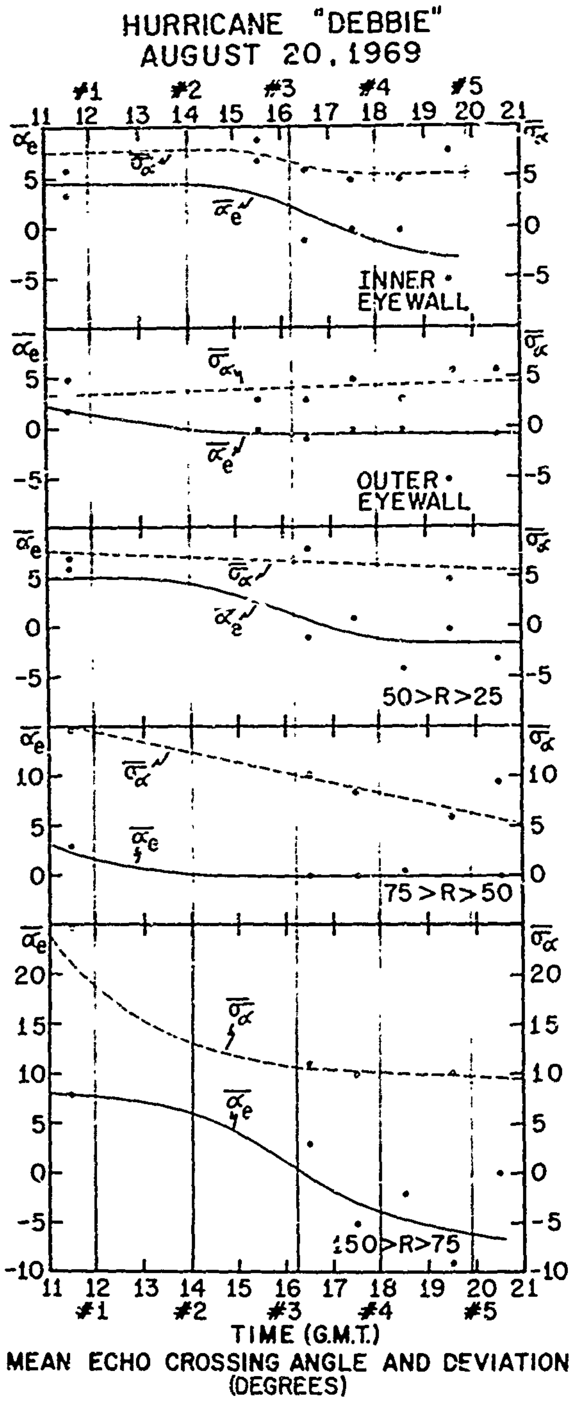


Figure J-7. Azimuthally averaged echo crossing angles at selected range intervals together with the mean maximum deviations about the azimuthal mean. Scale for the mean values (solid circles) is on the left and the scale for the deviations (open circles) is on the right. The thin vertical lines indicate the seeding times.

(5) When the echo speed deviations from the mean were plotted as a function of azimuth, wave number 2 appeared to be the dominant wave number at all radius intervals and time periods studied. This was true also when the crossing angle deviations were plotted as a function of azimuth.

(6) The general tendency was for the positive echo speed deviations in the outer three range intervals to be located in the front and right rear quadrants with negative deviations in the right front and left quadrants, as shown in figure J-8.

(7) The phase of the crossing angle deviations was almost exactly one-half wavelength out of phase with the speed deviations in each of the outer three range intervals. This meant that negative crossing angle deviations (outward moving echoes) were most common in the left front and rear quadrants, with positive crossing angle deviations (inward moving echoes) located in the rear and right front quadrants. This means that the speed maxima and minima are located at the position of zero crossing angle. Likewise, the maximum inward and outward crossing angles occur at the mean echo speed. Furthermore, as the echo speed is decelerating downstream the crossing angle is outward, and as the echo speed is accelerating downstream, the crossing angle is inward.

(8) Figure J-9 illustrates how the speed and crossing angle deviations around the inner and outer eyewalls tended to rotate cyclonically with time nearly matching the rotation rate of the major axis as described by Black et al. (1971). Following each of the last three seedings the relative location of the major axis, speed maximum, and crossing angle maximum changed as each decelerated by different amounts during the time period from 15 minutes after seeding to 1 hour after seeding and then accelerating, maintaining their new phases until the next deceleration. The significance of this is not known at present. However, it seems quite significant that, except for the period of about an hour after each seeding, the rate of rotation of the speed and crossing angle deviations nearly matches that of the major axis.

(9) The relation between the phases of the speed and crossing angle deviations was not as clear-cut as the outer radius intervals, but generally the speed maxima corresponded with crossing angle minima (outward motion).

(10) The faster moving, outward moving echoes in the inner and outer eyewall regions tended to be correlated with more solid looking echoes when compared with a PPI radar composite at the same time interval, while the slower moving, inward moving echoes tended to be correlated with the portion of the eyewall broken into individual cells, which tended to protrude into the eye occasionally. This

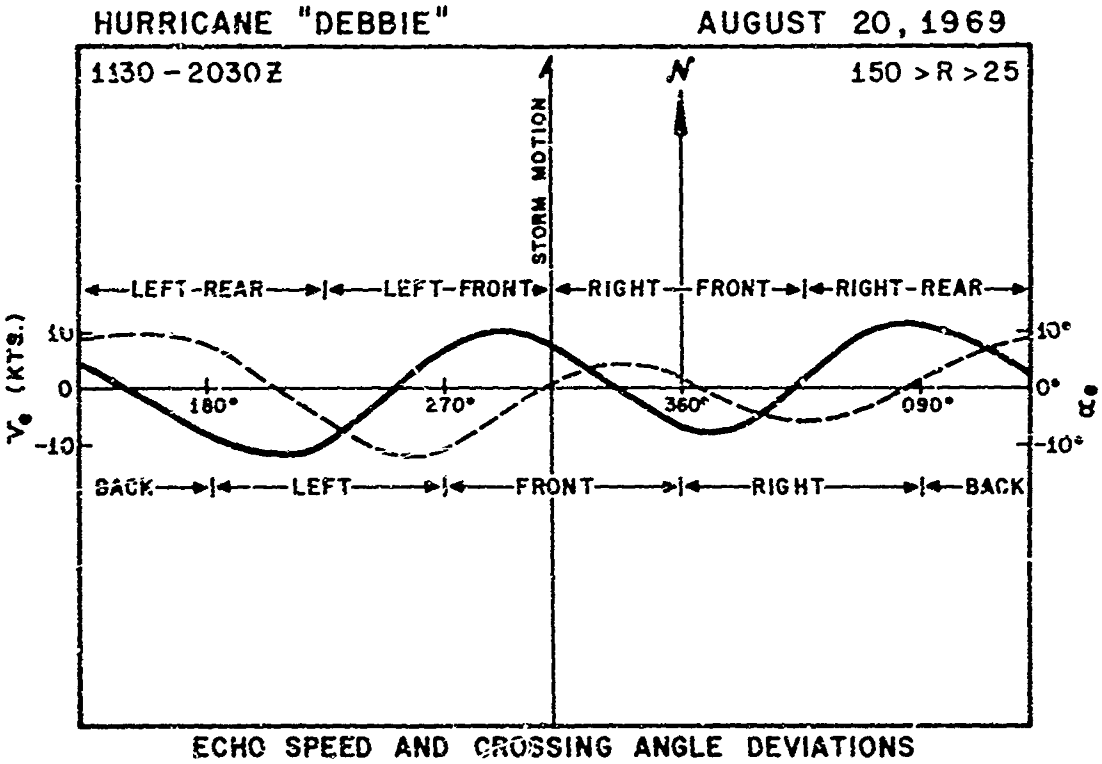


Figure J-8. Azimuthal variation of echo speed (solid curve) and crossing angle (dashed curve) beyond the eyewall during the time period studied.

result is in agreement with echo velocity analyses of the eyewall region of Hurricane Carrie by Fujita (1959), of Hurricane Daisy by Jordon (1960), and of Hurricane Celia by Fujita (1971).

CONCLUSIONS

Further study is needed relating the horizontal asymmetries in the low- and middle-level motion fields to the asymmetric structure of the radar echoes and their motion with time. It is anticipated that further study of the motion of radar echoes in a hurricane should yield relationships between preferred regions of convergence and divergence and the appearance of radar echoes at a given time, especially in the eyewall region. If such a relationship is forthcoming, it might greatly improve the implementation of hurricane seeding

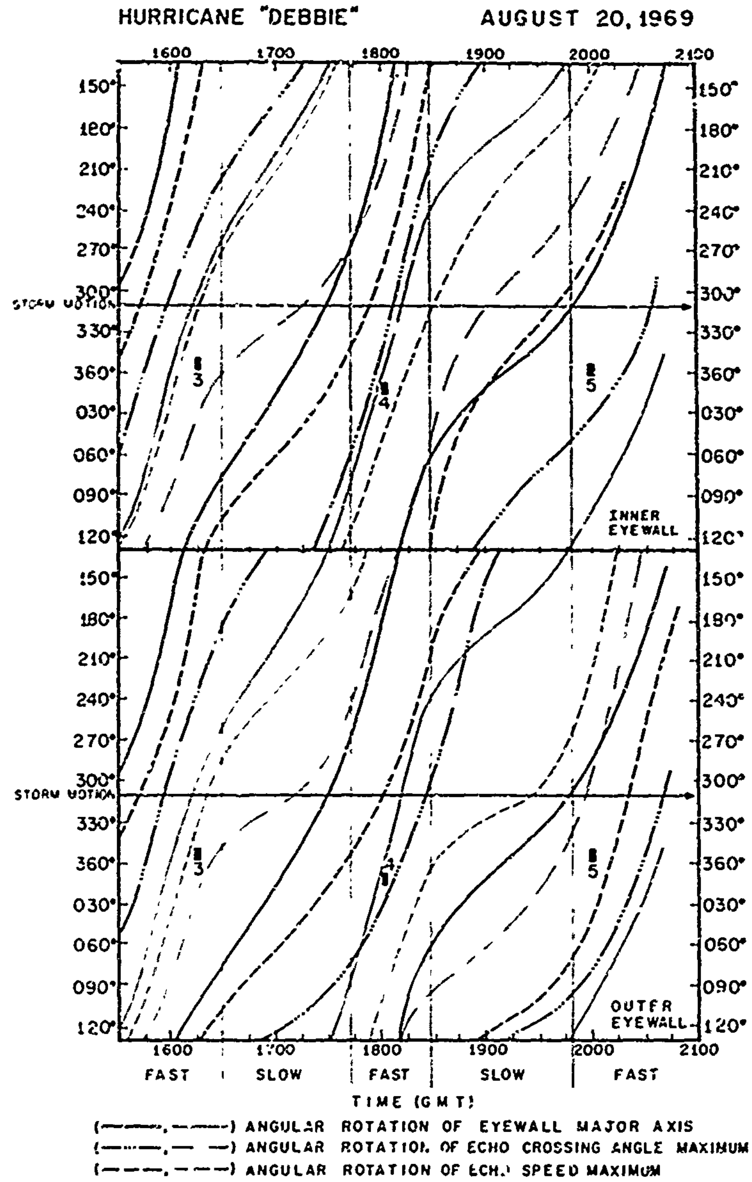


Figure J-9. Angular rotation of the eyewall major axis initially in the front quadrant together with the echo speed and crossing angle maxima initially just upstream from this major axis position are all indicated by thick lines. The position of the major axis initially in the rear quadrant together with the echo speed and crossing angle maxima just upstream are indicated by thin lines.

The top panel is the rotation rates for the inner eyewall and the bottom panel is the rotation rates for the outer eyewall. Black retangles indicate the seeding time and location for the third, fourth, and fifth seedings. Thin vertical lines delineate the slow moving time periods following each seeding from the fast moving time periods.

experiments since the appearance of the eyewall region on radar could then be used to direct seeding aircraft to the locations where the seeding agent will be most effective.

REFERENCES

Black, P. G., J. J. O'Brien and B. M. Lewis (1967): Ocean motion beneath a hurricane and its influence on the operation of airborne Doppler radar. Fifth Technical Conference on Hurricanes and Tropical Meteorology, Caracas, Venezuela, November.

Black, P. G., H. V. Senn and C. L. Courtright (1971): Some airborne radar observations of precipitation tilt, bright band distribution and eye configuration changes during the 1969 multiple seeding experiments in Hurricane Debbie. Submitted to *Monthly Weather Review.*

Fujita, T. T. (1959): A computation method of velocity of individual echoes inside hurricanes. Final Report CWB 9530, May, 7 pp.

Fujita, T. T., and H. Grandoso (1968): Split of a thunderstorm into anticyclonic and cyclonic storms and their motion as determined from numerical model experiments. *Journal of Atmospheric Sciences, 25,* (3), May, pp. 416-438.

Fujita, T. T. (1971): private communication.

Gentry, R. C., T. T. Fujita and R. C. Sheets (1970): Aircraft, spacecraft, satellite and radar observations of Hurricane Gladys, 1968. *Journal of Applied Meteorology, 9,* (6), December, pp. 837-850.

Grocott, D. F. H. (1963): Doppler correction for surface movement. *Journal of the Institute for Navigation, 16,* pp. 57-63.

Hawkins, H. F. (1971): Comparison results of the Hurricane Debbie, 1969, modification experiments with those from Rosenthal's numerical model simulation experiments. *Monthly Weather Review, 99,* (5), May, pp. 427-434.

Jordon, C. L. (1960): Spawinds for the eyewall of Hurricane Daisy of 1958. *Proceedings of the Eighth Weather Radar Conference,* April 11-14, pp. 219-226.

Ligda, M. G. H. (1955): Analysis of motion of small precipitation areas and bands in the hurricane of August 23-28, 1949. *Technical Note No. 3*, Massachussets Institude of Technology, 41 pp.

Rosenthal, S. L. (1971): A circularly symmetric, primitive equation model of tropical cyclones and its response to artificial enhancement of the convective heating function. *Monthly Weather Review, 99*, (5), May, pp. 414-426.

Ross, D. (1971): private communication.

Senn, H. V. (1960): The mean motion of radar echoes in the complete hurricane. *Proceedings of the Eight Weather Radar Conference*, April 11-14, pp. 427-434.

Senn, H. V., H. W. Hiser and R. D. Nelson (1960): Studies of the evolution and motion of radar echoes from hurricanes. Final report, U.S. Weather Bureau, *Report No. 8944-1*, August.

Senn, H. V. (1963): Radar precipitation echo motion in Hurricane Donna. *Proceedings of the Third Technical Conference on Hurricanes and Tropical Meteorology*, June 6-12.

Senn, H. V., and J. A. Stevens (1965): A summary of empirical studies of the horizontal motion of small radar precipitation echoes in Hurricane Donna and other tropical storms. Technical Note 17-NHRL-74, November, 55 pp.

Senn, H. V. (1966): Precipitation shear and bright band observations in Hurricane Betsy, 1965. *Proceedings of the Twelfth Weather Radar Conference*, American Meteorological Society, October, pp. 447-453.

Watanabe, K. (1963): Vertical wind distribution and weather echo (in the case of the typhoon). *Proceedings of the Tenth Weather Radar Conference.* April 22-25, pp. 222-225.

APPENDIX K

A SUMMARY OF RADAR PRECIPITATION ECHO HEIGHTS IN HURRICANES

Harry V. Senn
Rosenstiel School of Marine and Atmospheric Science
University of Miami

INTRODUCTION

In recent years the need for three-dimensional radar precipitation data in hurricanes has increased greatly. This is due partly to requirements of the National Weather Service for such information on existing storms, partly to satisfy the interests of those who must reconnoiter the storms with aircraft, but most importantly to fill gaps in the knowledge necessary for intelligent planning and execution of attempts to significantly modify hurricanes.

A large amount of height data and many case histories are available for various types of storms which occur over the United States because of the presence of radars capable of making observations. Some land-based RHI data on hurricanes exist for storms approaching or over land, but these cases are not typical of over-water situations in the tropics. Furthermore, such data are rarely obtained with radars having optimum vertical beamwidths (1 degree or less), transmitting frequencies, peak power, or data recording equipment. For instance, in several hurricanes which affected the southeast coast ot Florida, each of the WSR-57 radars at Miami and Key West obtained only two or three Polaroid RHI photographs for later analysis. The sparsity of RHI data was due to lack of automatic data gathering equipment. During the same period, many days of routine, excellent PPI data were collected.

Unfortunately, RHI data for hurricanes farther from land are even more limited. Although nearly optimum airborne equipment has existed for almost two decades, Project STORMFURY impetus was necessary before the APS-45 radars aboard the WC-121N reconnaissance aircraft were capable of obtaining documented RHI data useful to researchers.

The following is an attempt to summarize the RHI data from all sources on hurricanes in an attempt to arrive at a model which might be used to help determine where one might profitably direct modification efforts.

HURRICANES PRIOR TO 1958

Early observations by Wexler (1947), Ligda (1951), Jordan and Stowell (1955) either do not even mention radar echo top observations or they report on heights in a single narrow area of interest without indicating the general height population in hurricanes. Probably the most complete early report on echo heights was by Kessler and Atlas (1956) on Hurricane Edna, 1954, using the TPQ-6, FPS-4, and FPS-6 radars. However, the observations were made at latitudes and times in the life history of the storm that they were most probably not representative of hurricanes in more tropical latitudes.

HURRICANE DAISY, 1958

Jordan et al. (1960) presented many features of Hurricane Daisy, 1958, including some RHI radar data taken in and near the eyewall region. They found the maximum echo tops to be about 65,000 ft with echoes "away from the eye..." less than 45,000 ft. "Daisy" was a very well formed storm just northeast of the Bahama Islands at the time. The eye was open with classically clear blue skies above it, and the precipitation pattern fairly typical (Senn and Hiser, 1959) except for the fact that the eyewall was open to the west and the heaviest precipitation, as well as spiral bands, had rotated to the southern regions.

HURRICANE JUDITH, 1959

In 1960, Senn et al. presented RHI data taken on the University of Miami MPS-4 radar on minimal Hurricane Judith, 1959, a small, late season storm. However, "Judith" was not typical of most hurricanes in either PPI or RHI pattern configurations.

HURRICANE DONNA, 1960

Jordan and Schatzle (1961) published the first RHI picture of the eye taken on the U.S. Navy's APS-45 airborne radar when reporting on the "Double Eye of Hurricane Donna." Although the picture did not show it, they described the inner eyewall echo tops as 45,000 ft with the outer eyewall topped

near 30,000 ft. Using the land-based University of Miami's MPS-4 radar, Senn and Hiser (1961) presented the first comprehensive data on echo tops in a major storm at sub-tropical latitudes. Table K-1 summarizes the heights of 3709 echoes in the four quadrants of Hurricane Donna based on the direction of motion of the storm. (Since this was northerly during most of the period of observation, little difference would be apparent if the reference line were north.) It is interesting to note that over 95 percent of the echoes observed had tops of less than 30,000 ft and over 76 percent had tops below 20,000 ft. However, it is just as obvious that more than one-third of all echoes had tops above the melting level. Assuming this storm was typical with respect to bright band echoes, probably only a small fraction of those above the bright band were active towers; the rest had reached or passed the mature stages. In the absence of sufficient RHI data, Senn et al. (1963) attempted to use far more voluminous "Donna" PPI data using range variations to indicate approximate echo heights for comparisons with observed winds. The technique was somewhat rewarding in the absence of other better data but obviously did not produce echo heights to the accuracy limits of an RHI radar, so no detailed comparisons with other storm data are presented.

HURRICANE DEBRA, 1961

Bigler and Hexter (1960) used CAPPI techniques to show the echo coverage at "standard," 10,000, 20,000, and 30,000 ft levels in Hurricane Debra (1961) as viewed by the 3-cm CPS-9

Table K-1. Number of Echoes by Height, Range, and Quadrant From MPS-4 Radar, Hurricane Donna, 1960.

Quad.	0-89°				90-179°				180-269°				270-359°				TOTAL	OF
Range*	<45	55	65	75	<45	55	65	75	<45	55	65	75	<45	55	65	75		TOTAL
02-10	19	7	4	2	2	5	5	6	5	7	2	1	25	11	9	4	114	03.1
12-20	293	154	97	41	250	214	151	97	325	172	119	53	348	339	170	97	2801	75.5
22-30 **	76	33	27	12	85	55	27	9	100	32	36	11	79	52	44	23	701	18.9
32-40	8	8	9	4	3	2	4	9	4	0	1	2	4	6	0	1	66	01.8
42-50	2	5	4	2	2	6	0	0	1	0	1	0	0	2	0	0	25	00.7
TOTAL	398	207	141	61	345	282	187	121	435	211	159	67	456	291	223	125	3709	100.0

* Range from storm center nautical miles.
**HT.K'

FROM: Senn and Hiser (1961).

radar. Although this radar is subject to very appreciable attenuation in such situations, the data are interesting from several points of view. Very few echoes exceeded 30,000 ft. Some of those that did were in the northeast portion of the eye; others were 25 to 50 miles north; but the largest area is about 50 miles long and 50 miles west of the storm center. This is the area which has fewer and less intense echoes in normal storms (Senn and Hiser, 1959). However, "Debra" was under increasing influence from land areas and no longer typical of an over-water, undisturbed low latitude formation.

HURRICANE CLEO, 1963

Echo heights were studied by Senn (1965) in all regions of Hurricane Cleo again using the land-based University of Miami's MPS-4 radar. He found the median heights of echoes 30-40 miles from the storm center to be 20,000 ft with some cores in that region extending significantly higher. At greater ranges, heights were mostly lower; and nearer the eye the frequency of higher precipitation towers was greater. In the eyewall, towers generally exceeded 28,000 ft with some above 32,000 ft. Figures K-1 and K-2 are typical views of "Cleo" PPI and RHI data superimposed. In that study most active portions of spiral bands had tops on the order of 20,000 to 25,000 ft near the eye. Heights were 15,000 ft farther out in the rainshield, and generally the same in spiral band tails except for their cores which occasionally were found at 25,000 ft, once to 33,000 ft.

HURRICANE BETSY, 1965

Hurricane Betsy (1965) echoes were studied both from the land-based University of Miami's radars and the APS-45 airborne set by Senn (1966). In fact, this was the first comprehensive study of most quadrants and ranges of a storm in a completely over-water environment. Unfortunately, when the APS-45 RHI data were gathered on 1 September 1965, "Betsy" was a minimal hurricane gradually increasing in intensity. However, the Betsy precipitation pattern was much more normal than Cleo's in 1963. The Betsy echo heights occasionally exceeded 40,000 ft in the eyewall, and the echoes tended to be higher in the front of the storm; whereas, in Cleo they were higher in the right rear. Figures K-3 and K-4 show typical Betsy composites of echo heights superimposed on PPI presentations, and figures K-5 and K-6 show breakdowns of echo heights within 20 miles of the eyewall.

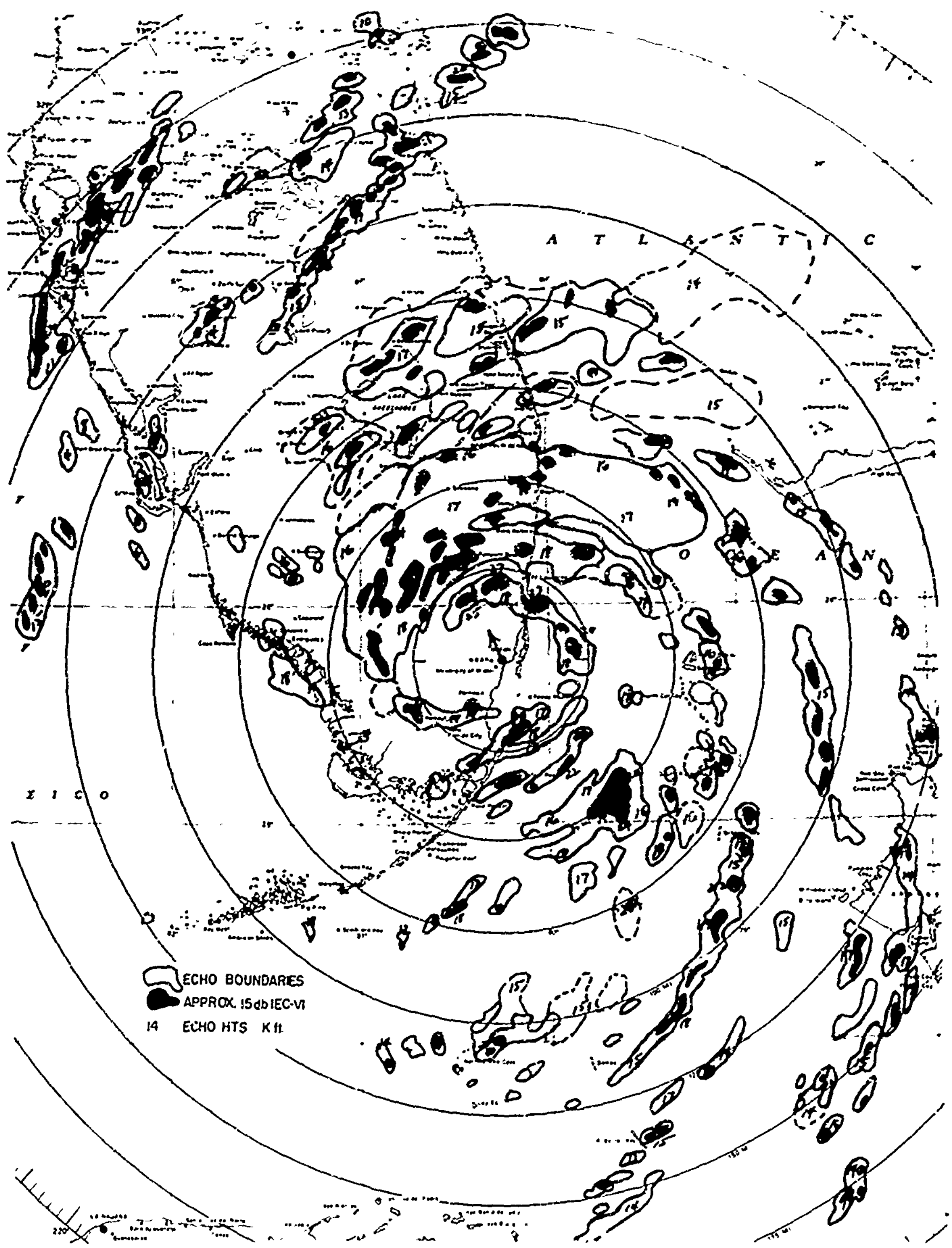


Figure K-1. Composite of typical PPI and RHI Cleo data 26-27 August 1964 from University of Miami MPS-4 radar.

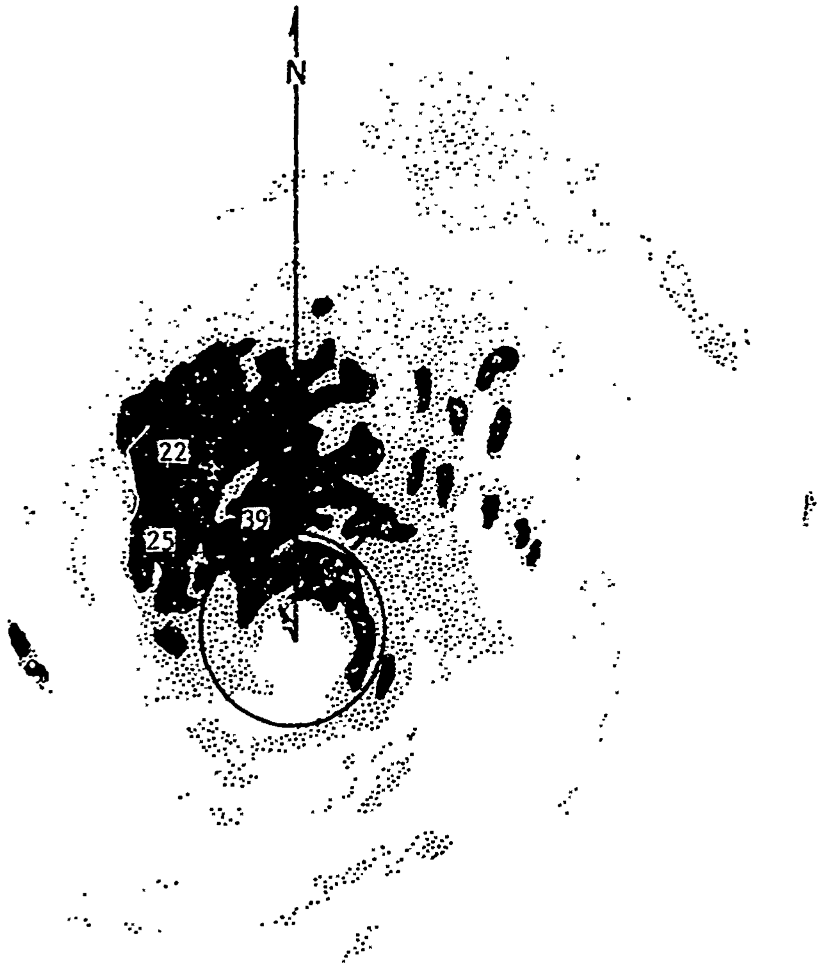


Figure K-2. Hurricane Cleo, 26 August 1964, 2130 EST, UM/10-cm PPI with IEC; heights in k ft from MPS-4; Circle includes eyewall precipitation; eye diameter 14 miles.

HURRICANE INEZ, 1966

Hurricane Inez (1966) echoes were also studied by Senn (1967) using an IEC device on the University of Miami's RHI radar. "Inez" was moving southwest toward the Florida Keys and was a most unusual, asymmetrical hurricane. Figures K-7 and K-8 show that some echoes exceeded 60,000 ft while almost all of the heaviest cores exceeded 20,000 ft. Almost the entire precipitation pattern consisted of a rather intense band of weather to the east and southeast of the storm center over the warm Straits of Florida waters with the entire western quadrants precipitation free. A further breakdown of

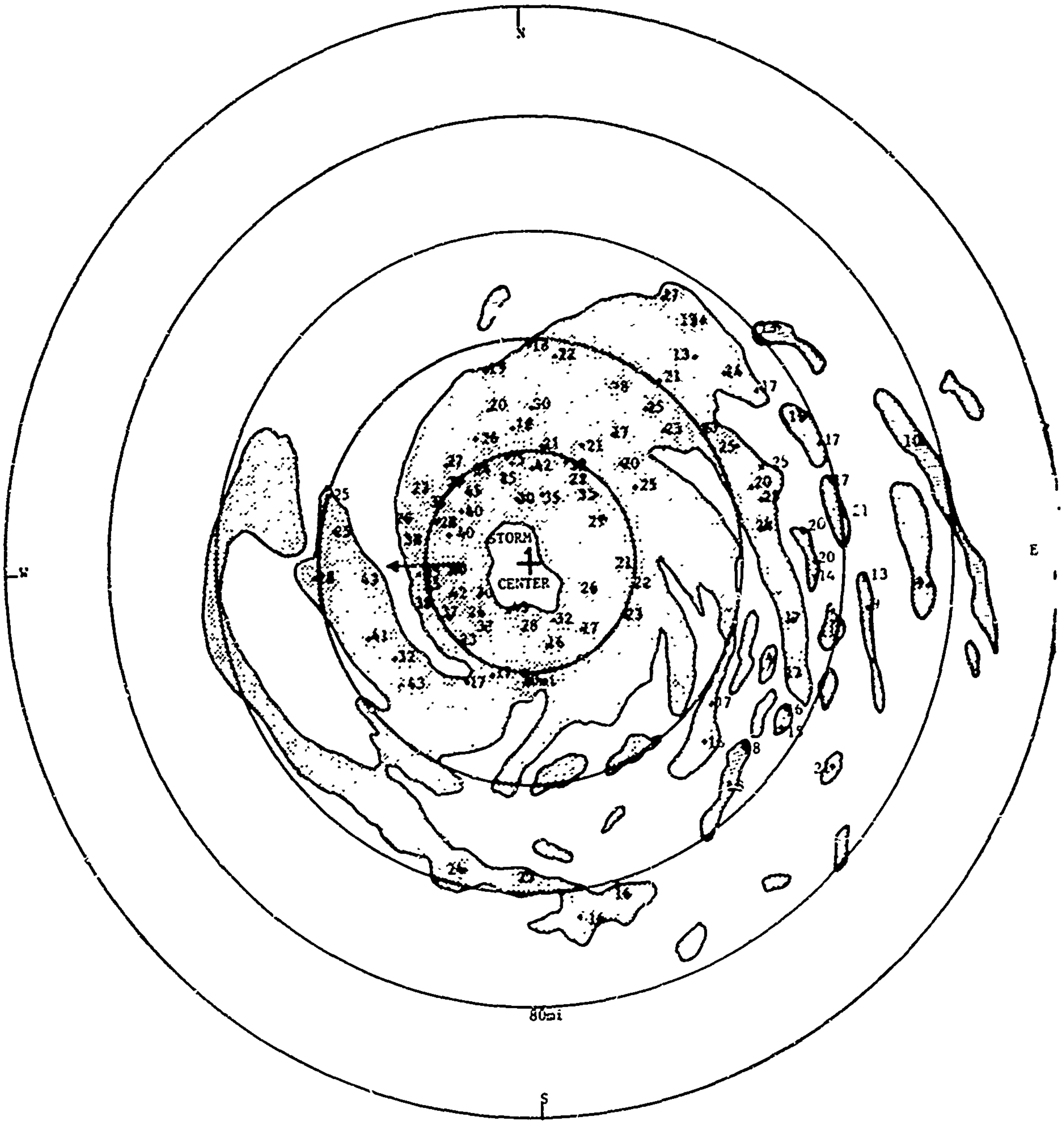


Figure K-3. Hurricane Betsy PPI with echo heights in k ft, APS-45, 1 September 1965.

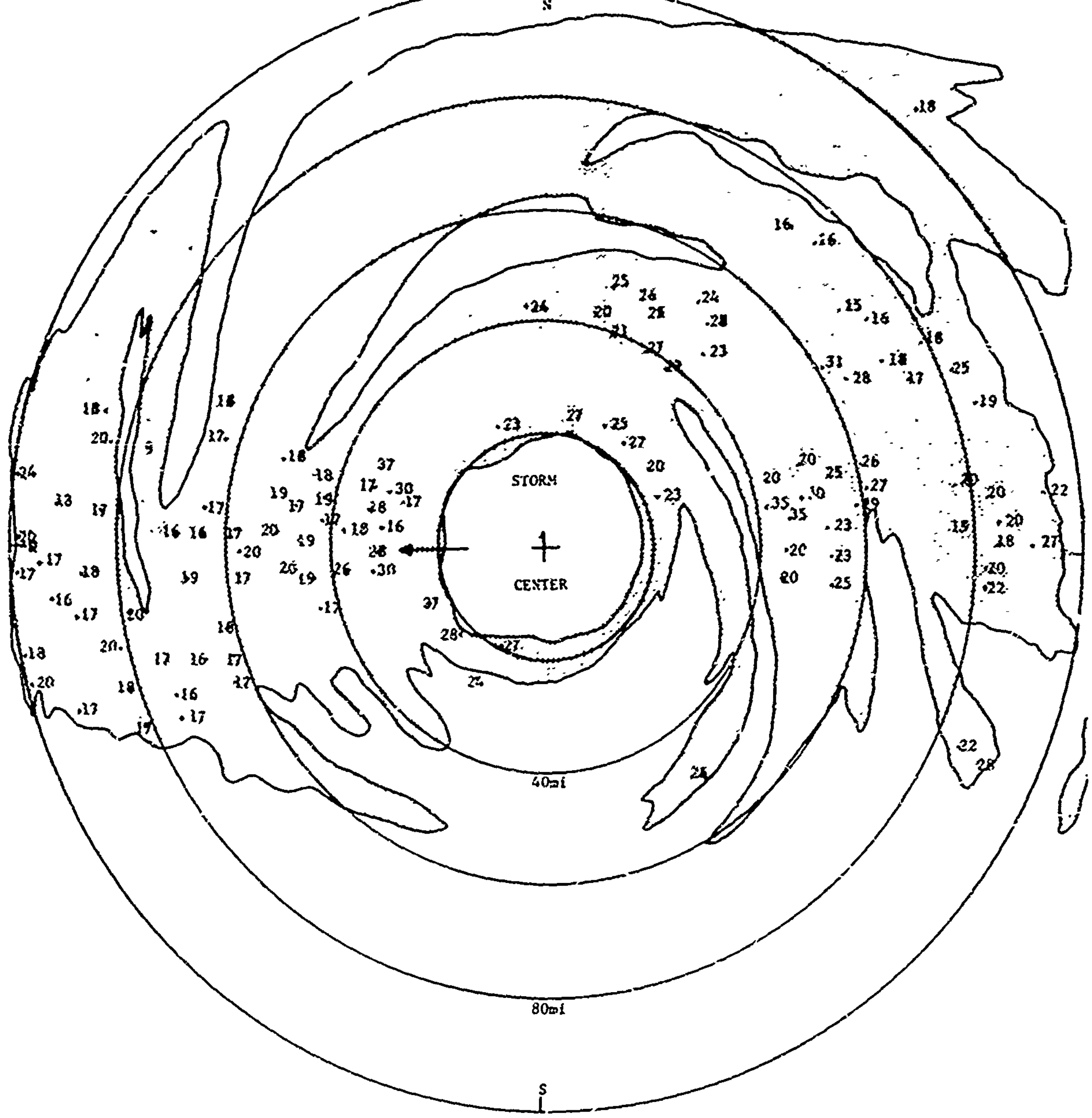


Figure K-4. Hurricane Betsy PPI with echo heights in k ft, MPS-4, 7 and 8 September 1965.

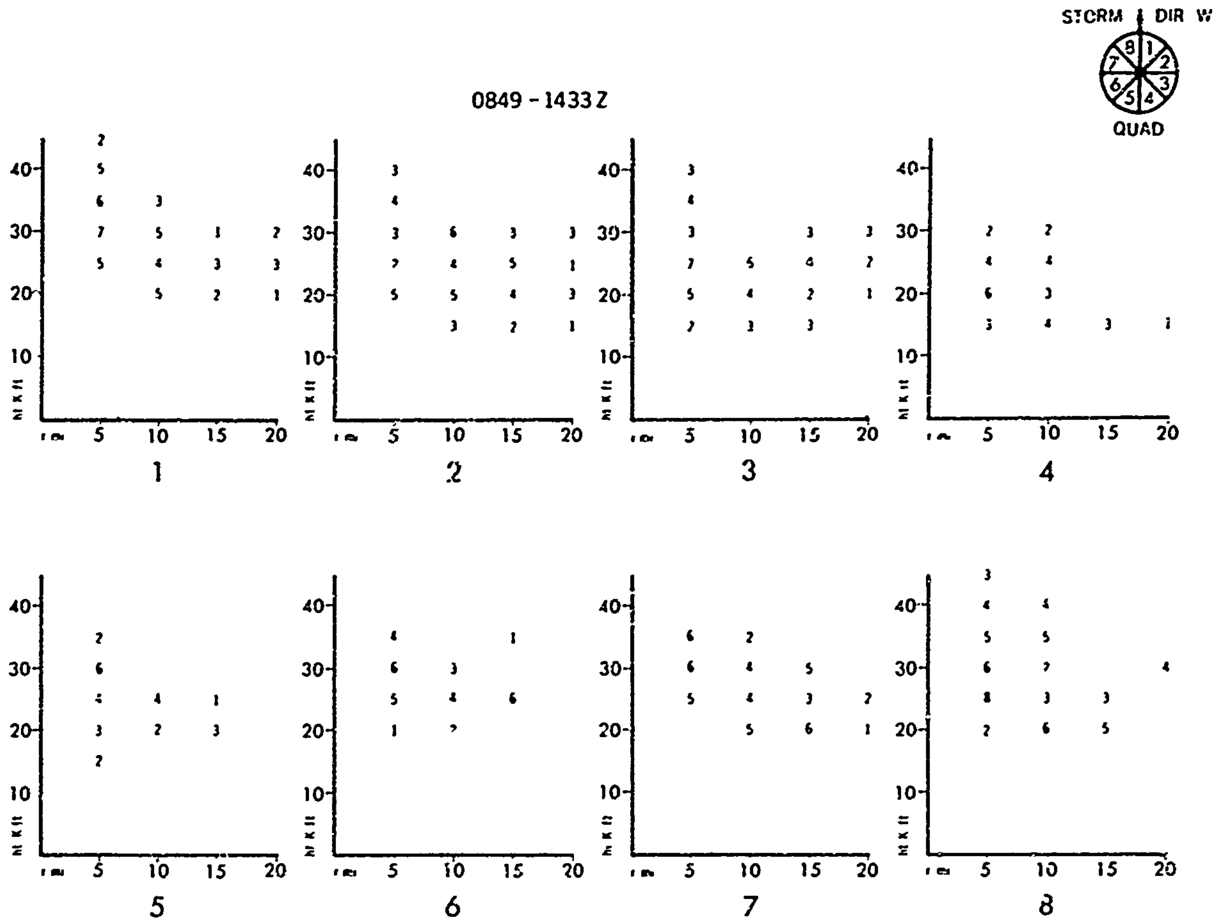


Figure K-5. Number and height of echoes within 20 miles of eyewall by quadrant in Hurricane Betsy, 1 September 1965, APS-45.

heights by quadrant and range within 20 miles of the eyewall was made using data from an earlier period northeast of Miami and these are shown in figure K-9.

HURRICANE FAITH, 1966, AND HURRICANES BEULAH AND HEIDI, 1967

Also underway is a study of echo tops in Hurricanes Faith (1966), Beulah and Heidi (1967) using the APS-45 data. However, these data are seriously lacking in important details and are expected to yield only general results. Some of these are discussed and shown in the summary.

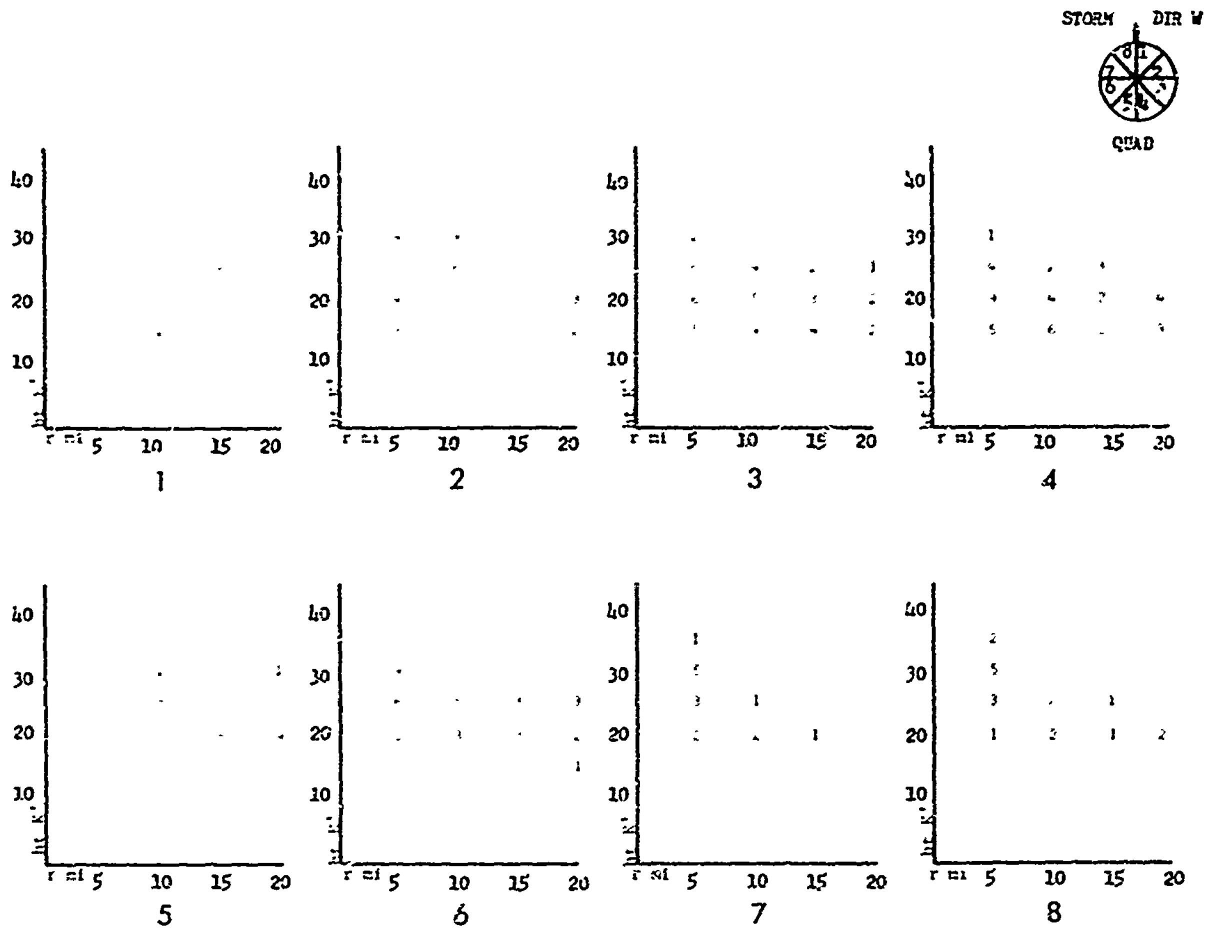


Figure K-9. Number and height of echoes within 20 miles of eyewall by quadrant in Hurricane Betsy, 8 September 1965, MPS-4, 0012-1140Z.

HURRICANE DEBBIE, 1969

Hurricane Debbie (1969) was studied by Senn and Courtright (1970), but results are only available for the eyewall region at present. These are shown on figures K-10 and K-11. A more complete study of the echo tops using the APS-45 airborne data is underway.

SUMMARY

Figure K-12 summarizes the number of echoes by height categories for five storms, all over water and below 26°N latitude. Note that the data are not comparable in the sense

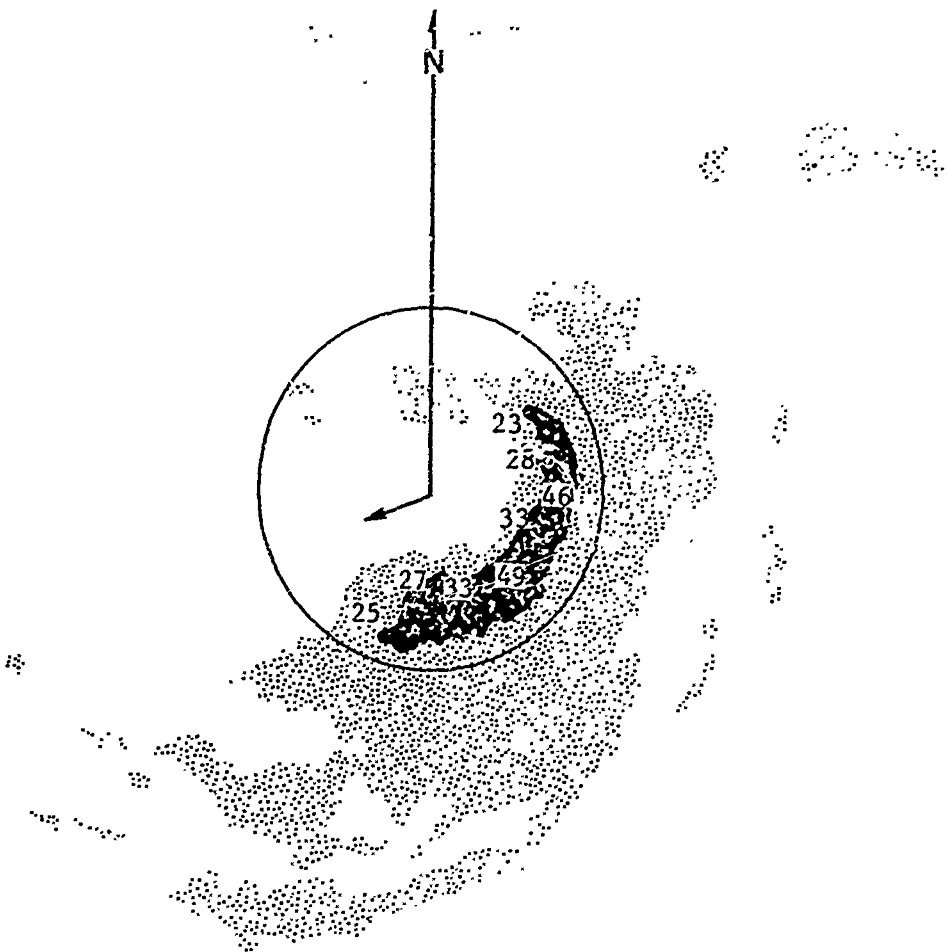


Figure K-7. Hurricane Inez, 4 October 1966, 0750 EST, UM/10-cm PPI with IEC; heights in k ft from MPS-4; circle includes eyewall precipitation; eye diameter 20 miles.

that although all echoes were found within 20 n miles of the eyewall (not the storm center), the number of echoes is a function of the flight path, quality of data collected, etc., as well as the actual height population produced in the storm. Consequently, the data for each category are also given in percentages of the total for that storm.

Although echoes penetrate significantly above 30,000 to 35,000 ft at greater ranges, a summary of the composite figures presented above shows that most of the taller echoes are within 20 n miles of the eyewall. Frequency distributions show the vast majority of all echoes to have tops in the 15,000 to 30,000 ft categories at all ranges. Generally, one should have no trouble finding echoes in the 20,000 to 25,000 ft category in and near the eyewall.

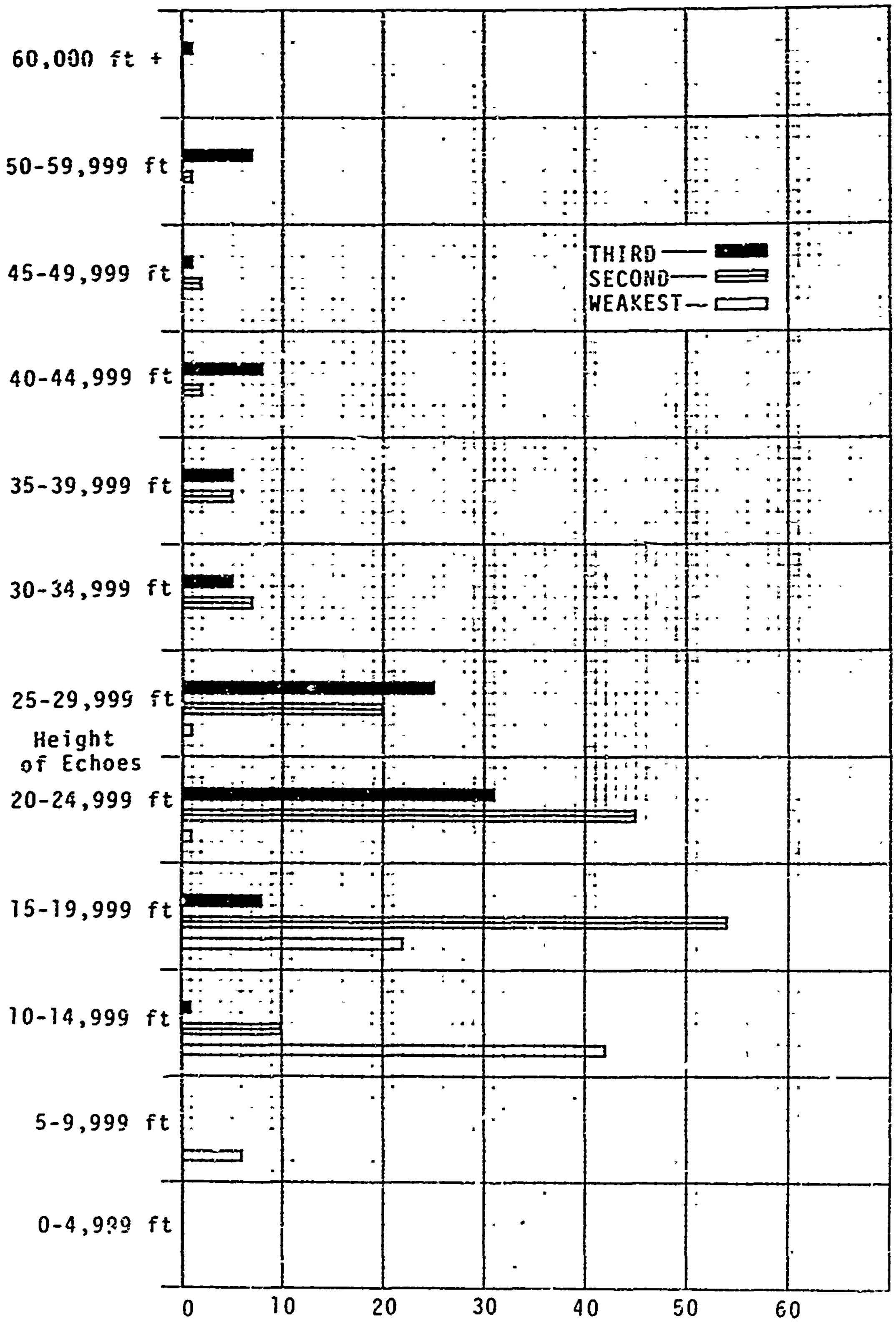


Figure K-8. Number and height of Hurricane Inez echoes in each of three iso-echo contour intensities.

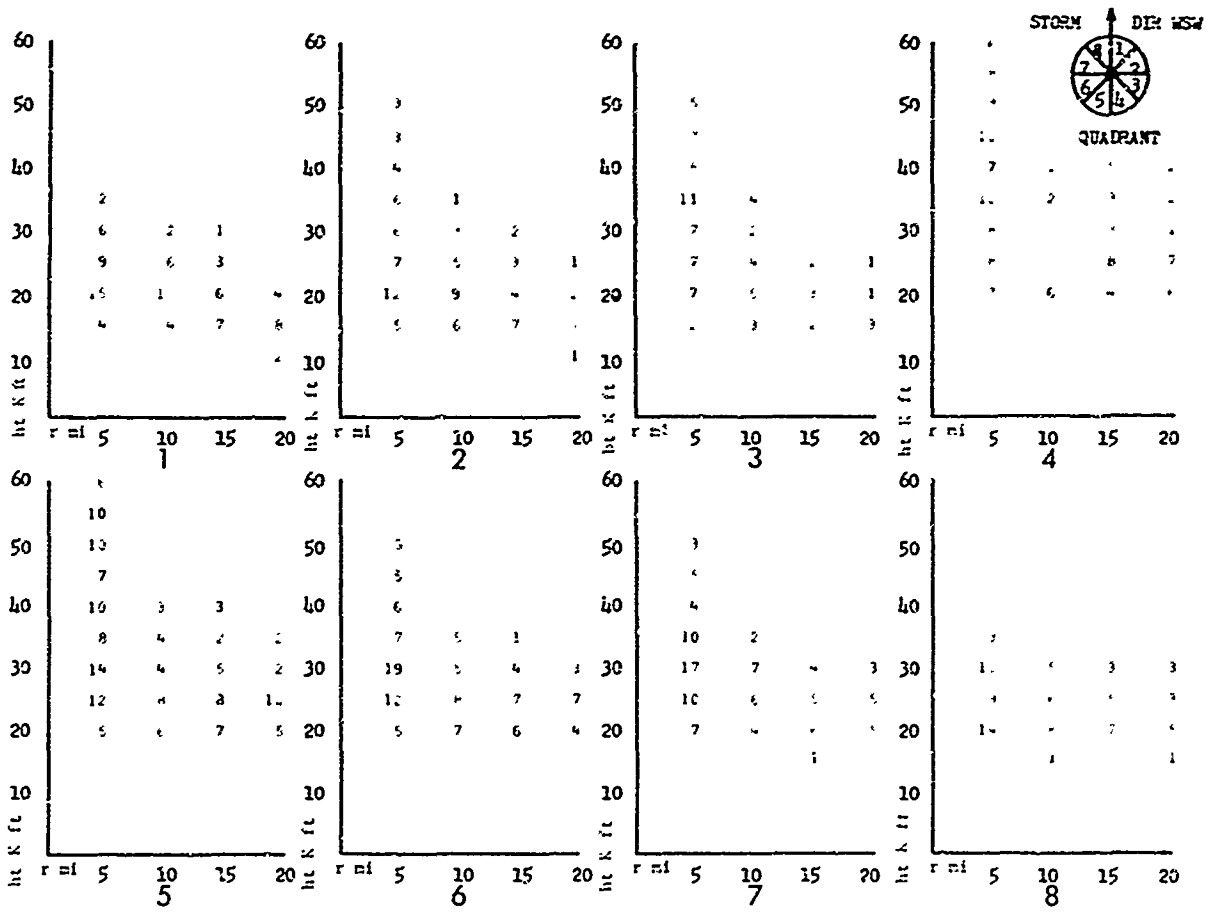


Figure K-9. Number and height of echoes within 20 miles of eyewall by quadrant in Hurricane Inez, 4 October 1966, MPS-4, 0030-2340Z.

Not shown in these figures, but deduced from earlier work, is the fact that, except when a storm is approaching land, the echo height populations remain relatively stationary with respect to the direction of storm motion rather than exhibiting a rotation around the storm center. It is not yet clear whether that also holds with respect to north, since most of the storms that could be considered representative were headed westerly or northerly when the observations were made. The tallest echoes, likewise, appear to be to the east and north of the storm center, and the south (or general rear) quadrants have the weakest, lowest echoes (sometimes not at all).

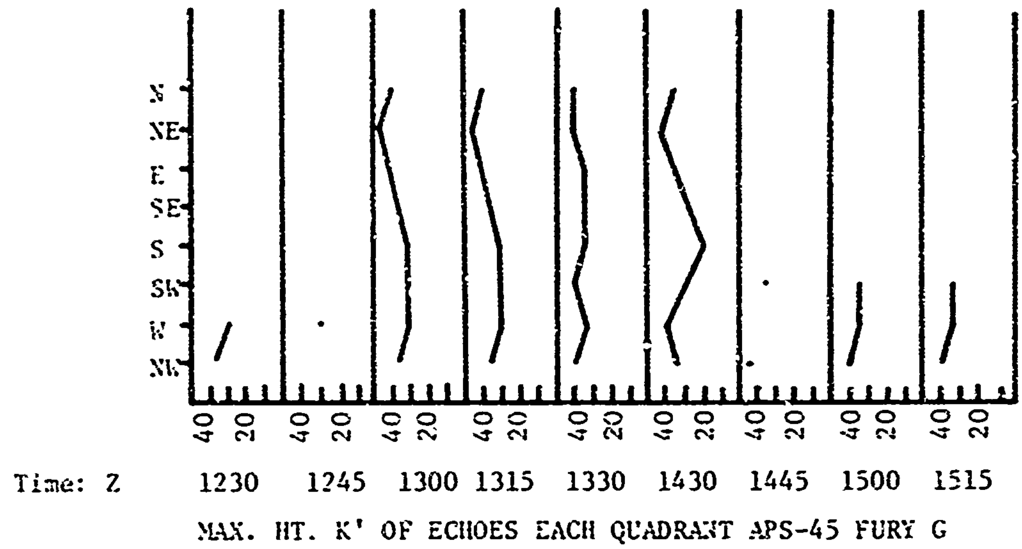


Figure K-10. Height of eyewall echoes, Hurricane Debbie 18 August 1969.

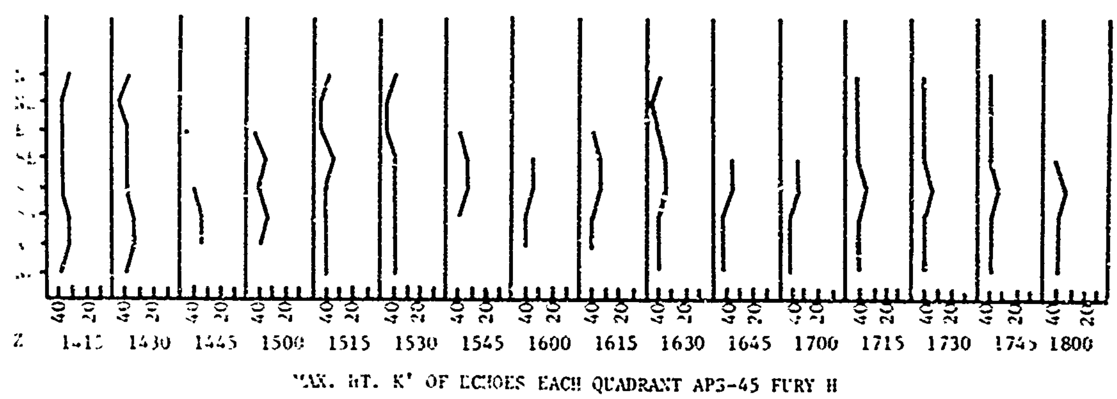


Figure K-11. Height of eyewall echoes, Hurricane Debbie 20 August 1969.

	≤15 K'	>15 K' ≤ 30 K'	>30 K'
Debbie F/H 8-20-69	86 (12%)	267 (38%)	351 ([illegible])
Debbie F/G 8-20-69	72 (13%)	213 (39%)	259 (48%)
Debbie F/G 8-18-69	51 (10%)	182 (38%)	249 (52%)
Heidi '67	51 (24%)	83 (39%)	77 (37%)
Beulah '67	32 (19%)	60 (36%)	74 (45%)
Faith '66	19 (16%)	58 (50%)	39 (34%)
Cleo '64	38 (22%)	71 (41%)	64 (37%)

Figure K-12. Number and percent of echoes by height within 20 miles of eyewall.

CONCLUSIONS

If one is looking for precipitation towers on the order of 20,000 to 25,000 ft outside the eyewall of a normal mature hurricane, he should find them in the north and east quadrants. A good RHI radar is a necessity, however, in a brief analysis of such clouds prior to any modification attempts since these quadrants are generally badly messed up by multi-layers of clouds, ample regions of "bright bands" (indicating melting hydrometers), etc., which make action purely on the basis of visual observations subject to uncertainty.

In fact, some of the above data lead to some rather perplexing questions regarding the seeding hypothesis used in Project STORMFURY. We have found the bright band in most quadrants and ranges of several hurricanes, as indicated in another paper in process. The results above show widespread echoes at heights where one expects glaciation, and certainly high level reconnaissance photos and satellite observations show an abundance of cirrus. However, one is also impressed with the general convective nature most echoes have on the RHI scope, many times in close proximity to the bright band. These observations suggest that echoes exist in all stages of generation and dissipation; but they do little to help answer the question of whether there is enough mixing of ice nuclei in the wall cloud regions of interest to significantly alter the possible effects of seeding active towers there. The results above show widespread echoes at heights where one expects glaciation, and certainly high level reconnaissance photos and satellite observations show an abundance of cirrus. However, one is also impressed with the general convective nature most echoes have on the RHI scope, many times in close proximity to the bright band. These observations suggest that echoes exist in all stages of generation and dissipation; but they do little to help answer the question of whether there is enough mixing of ice nuclei in the wall cloud regions of interest to significantly alter the possible effects of seeding active towers there.

Unfortunately, it is not possible to draw a series of PPI-RHI composites for any storm found in a relatively undisturbed tropical over-water environment simply because the data are too limited to date. Consequently, it seems essential that every effort be made to obtain such records with the only airborne radar presently capable of gathering high quality RHI data, the Navy APS-45. Secondarily, more effort should be made to gather RHI data on WSR-57's, the new WMO supplied RC-32B weather radars in the Lesser Antillies, and others, in an attempt to better describe this most important hurricane precipitation pattern dimension, including the bright band and shear in every sector of the storm.

REFERENCES

Bigler, S. G., and P. L. Hexter, Jr. (1960): Radar analysis of Hurricane Debra. *Proceedings 8th Weather Radar Conference,* American Meteorological Society, Cal., April, pp. 25-32.

Jordan, C. L., D. A. Hurt, and C. A. Lowrey (1960): On the structure of Hurricane Daisy on 27 August 1958. *Journal of Meteorology*, American Meteorological Society, *17*, pp. 337-348.

Jordan, C. L., and F. J. Schatzle (1961): The 'Double Eye' of Hurricane Donna. *Monthly Weather Review, 89*, (9), September, pp. 354-356.

Jordan, H. M., and D. J. Stowell (1955): Some small-scale features of the track of Hurricane Ione. *Monthly Weather Review, 83*, (9), September, pp. 210-215.

Kessler, E., and D. Atlas (1956): Radar-synoptic analysis of Hurricane Edna, 1954. *Geophysical Research Papers No. 50*, A.F.C.R.L., Bedford, Mass., July, p. 113.

Ligda, M. G. H. (1951): Radar storm detection. *Compendium of Meteorology*, American Meteorological Society, Boston, Mass., pp. 1265-1289.

Senn, H. V. (1963): Radar precipitation echo motion in Hurricane Donna. *Proceedings 3rd Technical Conference on Hurricanes and Tropical Meteorology*. A.M.S., A.G.I., and M.G.I. and M.G.U., Mexico City, Mexico, June 6-12, R.S.M.A.S. Contr. No. 463.

Senn, H. V. (1965): The three-dimensional distribution of precipitation in Hurricane Cleo. *4th Technical Conference on Hurricanes and Tropical Meteorology*. A.M.S., Miami Beach, Fla., November.

Senn, H. V. (1966): Precipitation shear and bright band observations in Hurricane Betsy, 1965. *Proceedings 12th Weather Radar Conference*, October 17-20, Oklahoma City, Okla., R.S.M.A.S. Contr. No. 710.

Senn, H. V. (1967): Radar Hurricane Research, Final Report, ESSA, NHRL Contract No. E22-84-67(N), *Report No. 8208-1*, September, DDC AD 821-860.

Senn, H. V., and H. W. Hiser (1959): On the origin of hurricane spiral bands. A.M.S., *Journal of Meteorology, 16*, (4), August, pp. 419-426, R.S.M.A.S. Contr. No. 215.

Senn, H. V., H. W. Hiser, and R. D. Nelson (1960): Studies of the evolution and motion of radar echoes from hurricanes 1 July 1959 to 30 June 1960, Final Report. U.S. Weather Bureau, Contract CWB-9727, *Report No. 8944-1*, August.

Senn, H. V., and H. W. Hiser (1961): Effectiveness of various radars in tracking hurricanes. *Proceedings 2nd Technican Conference on Hurricanes*, A.M.S., Miami Beach, Fla., June, pp. 101-114, R.S.M.A.S. Contr. No. 318.

Senn, H. V., and C. L. Courtright (1970): Radar Hurricane Research, Final Report, ESSA, NHRL, Contract No. E21-41-70(N), October.

Wexler, H. (1947): Structure of Hurricanes as determined by radar. *Annals of N.Y. Academy Sciences, 48*, September 15, pp. 821-944.

APPENDIX L

PROJECT STORMFURY EXPERIMENTAL ELIGIBILITY IN THE WESTERN NORTH PACIFIC

William D. Mallinger
National Hurricane Research Laboratory

INTRODUCTION

Project STORMFURY, the interagency project for hurricane modification experiments, was formally organized in 1962. Since that time the operating areas authorized and the eligibility rules have been changed several times progressively toward further relaxations of the seeding restrictions. The rules for this area eligibility for seeding were last changed in 1970 and are now as follows: "A storm or hurricane in the southwest North Atlantic, the Caribbean Sea, or the Gulf of Mexico is eligible for seeding as long as the forecast states that there is a small probability (10 percent or less) of the hurricane coming within 50 n miles of a populated land area within 18 hours after seeding." To date only the Atlantic Ocean area has been utilized to seed the three hurricanes upon which experiments have been conducted (Esther, 1961; Beulah, 1963; and Debbie, 1969).

Studies of statistical probabilities of eligible hurricanes and typhoons under the older eligibility rules were made and published in the STORMFURY Annual Reports for 1968 and 1969. These reports covered the Atlantic, Caribbean, and Gulf of Mexico areas; the eastern Pacific hurricane regions; and the western North Pacific area. The hurricanes occurring in the eastern North Pacific area (off the west coast of Mexico) are not considered to be suitable experimental targets for STORMFURY seeding and will not be further discussed in this report. An update to include 1970 cases under the new 18-hour rule for the Atlantic areas will be included for purposes of comparison with the seeding opportunities in the Western Pacific. This comparison is particularly important because proper bases for operations in the Pacific are needed if there is to be a sufficient increase in experimental opportunities to justify the Project's move to the Pacific.

ATLANTIC OCEAN, CARIBBEAN SEA, AND

GULF OF MEXICO STORMFURY AREAS

Figure L-1 shows the eligible areas for seeding used from 1968 through 1970. Table L-1 shows the number of occurrences of hurricanes eligible for STORMFURY experiments during the months of August, September, and October from 1954 through 1970 using the "18-hour after seeding" eligibility rule. The addition of the storms which became eligible under the change from the "24-hour" to "18-hour" rule adds three storms to the Atlantic, two to the Gulf of Mexico, and one to the Caribbean. These additions increased the expected opportunities per year from an average of approximately 2 to 2.35 hurricanes per year eligible for seeding under the current seeding eligibility rules regarding position of the storm.

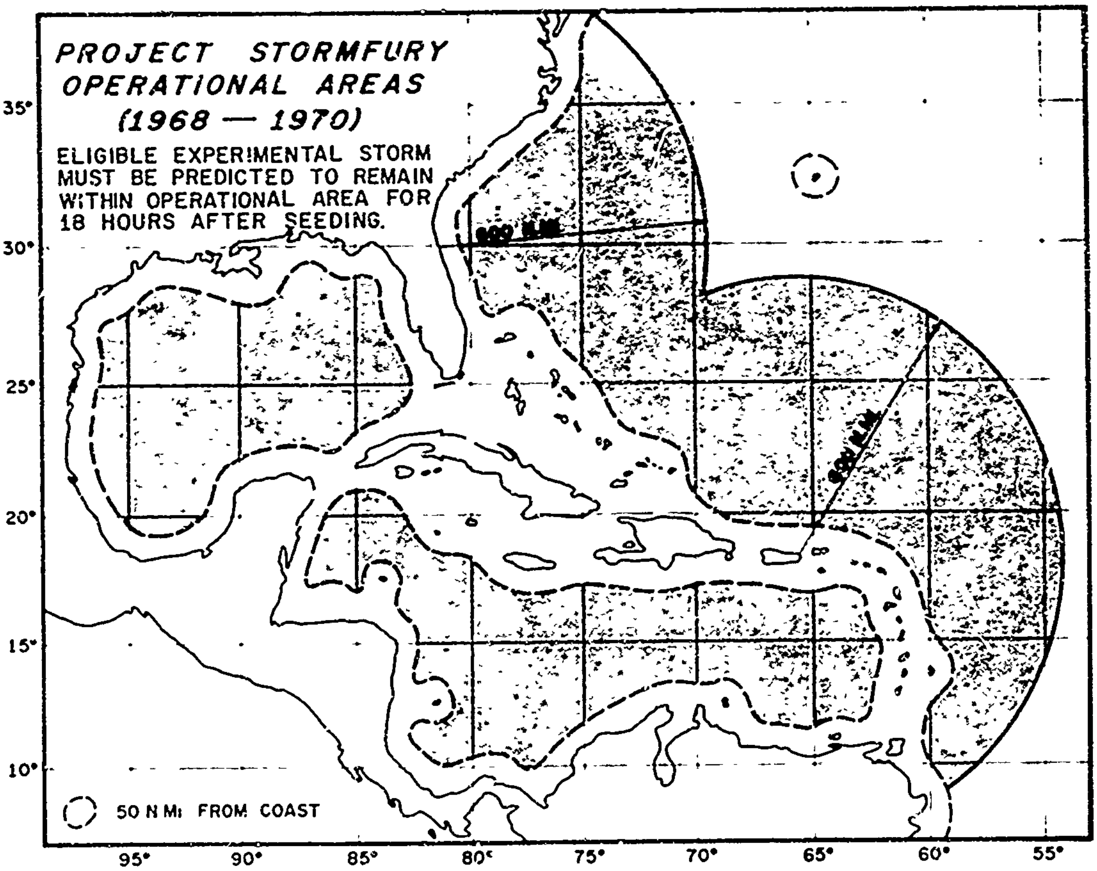


Figure L-1. Project STORMFURY operational areas (1968-1970). Eligible experimental storm must be predicted to remain within operational area for 18 hours after seeding.

Table L-1. Annual Frequency of Hurricanes Eligible for Seeding Between 1 August and 31 October Under Forecasting Techniques Criteria Approved for STORMFURY Operations Subsequent to 1970.

Year	Atlantic	Gulf of Mexico	Caribbean Sea	Total
1954	2	0	1	3
1955	4	0	1	5
1956	1	0	0	1
1957	1	0	0	1
1958	5	0	0	5
1959	2	0	0	2
1960	2	0	1	3
1961	2	1	0	3
1962	2	0	0	2
1963	3	0	1	4
1964	4	1	0	5
1965	2	0	0	2
1966	1	0	0	1
1967	0	0	0	0
1968	0	0	0	0
1969	2	1	0	3
1970	0	0	0	0
TOTAL	33	3	4	40

This number is misleading on the high side because some of these storms either had structure considered unsuitable for experimentation or were changing rapidly in intensity at the time and might not have been used for experiments even though they fell within the criteria established for area seeding eligibility. In addition, some of the storms considered eligible in the Gulf of Mexico and Caribbean Sea might not have been seeded for political reasons.

WESTERN NORTH PACIFIC

Figure L-2 shows the proposed operational areas if experiments are to be conducted from Guam *and* Okinawa. The eligibility rules considered in this study for the Western Pacific are: (1) The typhoon must be within 600 miles of the operations base for a minimum of 12 daylight hours, (2) maximum winds must be at least 65 knots, and (3) the predicted movement of the typhoon must indicate that it will not be within 50 n miles of a populated land area within 24 hours after seeding.

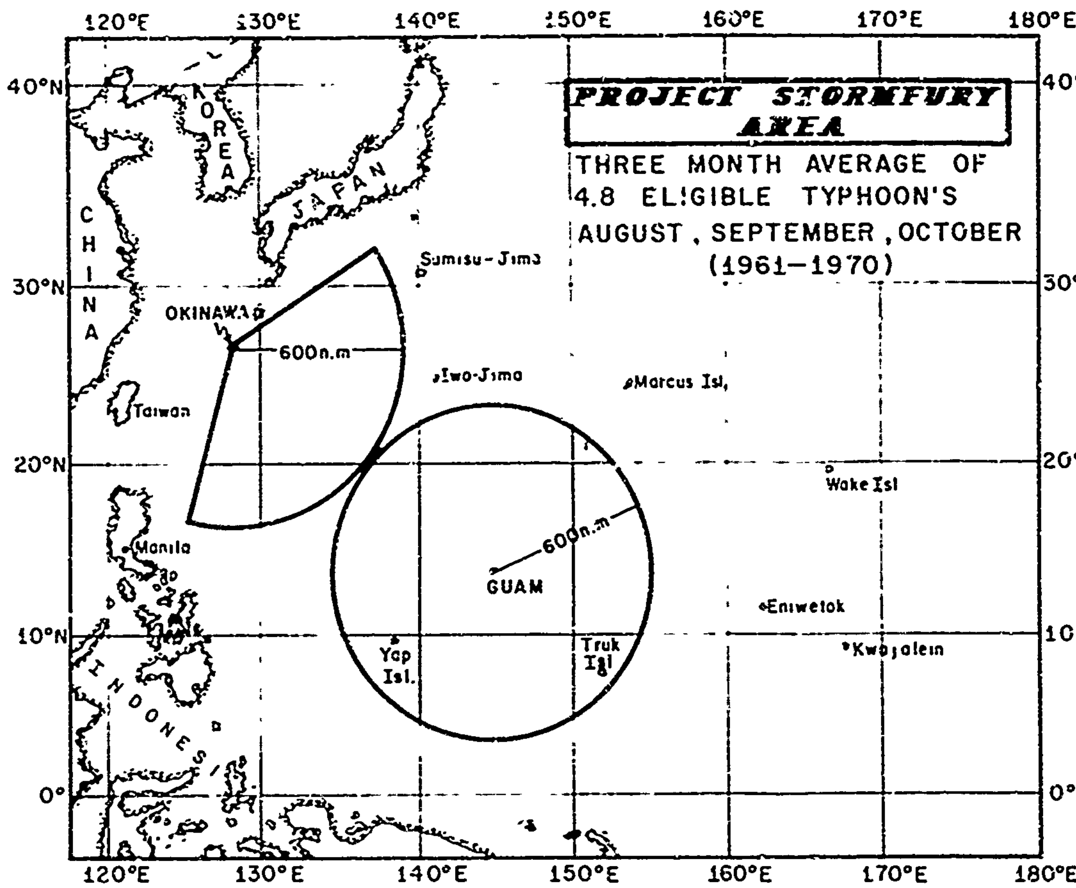


Figure L-2. Project STORMFURY area in the Western Pacific.

The list of Western Pacific typhoons eligible for seeding was updated to include 1970 tropical cyclones and was divided into two categories: (1) those that could be used for STORMFURY experiments with forces limited to operations from Guam only, and (2) those which permitted free use of either *Guam or Okinawa* from which to launch experiments (see table L-2).

Two of the 24 "Guam only" opportunities would have required such rapid reaction in order to mount a seeding experiment that they would probably have been missed. These storms formed within the 600 n mile radius of Guam and rapidly deepened while they continued to move out of the area. If a 48-hour notice to alert, deploy, and brief the participants in the experiment were required, both storms would definitely have been missed. A WP-3 or C-130 type aircraft might be used as a seeder in such cases when time does not permit the deployment of jet seeders to the operating base. If this is not feasible, STORMFURY monitoring missions without seeding might be conducted on shorter notice in these storms.

Table L-2. Western Pacific Typhoons Eligible for STORMFURY Experiments - August, September, and October (1961-1970).

Year	Guam Only	Combined use of Guam and Okinawa
1961	2	6
1962	3	7
1963	2	6
1964	1	2
1965	3	7
1966	1	3
1967	3	4
1968	5	8
1969	2	2
1970	2	3
TOTAL	24 (2.4[1])	48 (4.8[1])

[1] Number of storms per year

Seven of the 24 "Guam only" typhoons were also eligible later in their lives if forces operated from Okinawa. Several of these storms would have been eligible for seeding both from Guam and later from Okinawa, permitting two experiments on the same storm. It is also possible that a storm could be subjected to two experiments from either Guam or Okinawa although this opportunity occurs infrequently.

The free use of both Guam and Okinawa as STORMFURY bases of operation is essential to obtaining a suitable number of experiments during the 3-month period. Safety of personnel and aircraft is paramount and will require a multitude of decisions concerning the best and safest use of the STORMFURY forces. Examples of this are as follows: (1) A storm or typhoon approaching Guam from the east which, while eligible for experimentation, would not be seeded because forces would have to execute a typhoon evacuation (aircraft flyaway) for safety reasons. If these aircraft could be deployed to Okinawa for their evacuation, when the storm had passed Guam a mission could be mounted from Okinawa and terminated in Guam. Some changes in operational plans and techniques will be required to execute this type of experiment. (2) A typhoon that develops while approaching the 600 n mile radius to the west of Guam would be eligible in many cases if Project aircraft could terminate their missions in Okinawa. This also will require modified STORMFURY flight plans and schedules in order to accomplish the experiment.

If the flexibility of using both Guam and Okinawa as STORMFURY operational bases is not possible, opportunities to seed some of the storms would be lost because Project aircraft might have to fly away from Guam until an approaching typhoon had safely passed. Upon return of the forces to Guam and after mission preparations, the typhoon would have approached or exceeded the maximum operating range of STORMFURY forces.

The study was further expanded to examine the number of calendar days during which a large number of tropical cyclones exists in the Western Pacific to determine the effect that this factor would have on the availability and participation of reconnaissance aircraft for STORMFURY operations. Cyclone activity (tropical depressions, tropical storms, and typhoons) during the 3-month period of August, September, and October is listed by the number and percentage of days occurrence in table L-3.

During the months of August, September, and October tropical cyclones occur somewhere in the western North Pacific Ocean 84 percent of the time or an average of 77 days out of the 92. Three or more tropical cyclones occur simultaneously during an average of about 9 of these 77 days. Fortunately, during some of these periods, because of their location and strength, the tropical cyclones did not all require full reconnaissance coverage. Reconnaissance forces may be hard

Table L-3. Tropical Cyclone Days in Western North Pacific - August, September, October.

Year	Number of Days with 0 to 5 Cyclones					
	0	1	2	3	4	5
1960	8	41	22	14	4	3
1961	7	38	39	8	0	0
1962	15	23	39	15	0	0
1963	23	40	25	4	0	0
1964	10	42	29	11	0	0
1965	24	35	24	9	0	0
1966	11	40	25	16	0	0
1967	9	39	30	8	6	0
1968	15	31	37	9	0	0
1969	32	48	11	1	0	0
1970	8	60	23	1	0	0
TOTAL DAYS	162	437	304	96	10	3
AVERAGE DAYS	14.8	39.7	27.6	8.7	0.9	0.3
% OF DAYS	16.1	43.1	30.0	9.5	1.0	0.3

% of tropical cyclone days with one or two cyclones - 87.2
% of tropical cyclone days with three or more cyclones-12.8

pressed at times to participate in full scale Project STORMFURY experiments during periods when there are three or more active cyclones, but should be able to provide reconnaissance on one cyclone while participating in Project STORMFURY operations on another. There are exceptions to these assumptions; but, in general, sufficient forces to conduct experiments should be available during 68 of the 77 cyclone days. When, because of other commitments, DOD reconnaissance and seeder aircraft are not available to mount a full seeding experiment, the remaining available Project aircraft can be utilized to gather data on the natural variability within typhoons.

CONCLUSIONS AND RECOMMENDATIONS

(1) Conducting operations in the Western Pacific is worthwhile and should increase the number of experimental opportunities per average season by a factor of 2-3 over those experienced in the Atlantic regions provided that *both Guam and Okinawa* are available for use by STORMFURY forces. Addition of a base in the Philippines and in other locations in the Pacific adds a few opportunities per 10 years, but most of the eligible storms can be worked from either Guam or Okinawa. If Guam is available, but Okinawa is not, the desirability of moving the project to the Pacific should be reconsidered because of the limited increase in the number of expected opportunities over those in the Atlantic operating areas.

(2) During periods when there are three or more tropical cyclones occurring simultaneously (13 percent of the cyclone active periods during August, September, and October), monitoring missions could be conducted on suitable storms using fewer forces and without actual seeding.

(3) Some additional experiments could be conducted on tropical storms and tropical depressions during periods when no eligible typhoon activity was occurring.

GPO 836-595